NUCLEONICS

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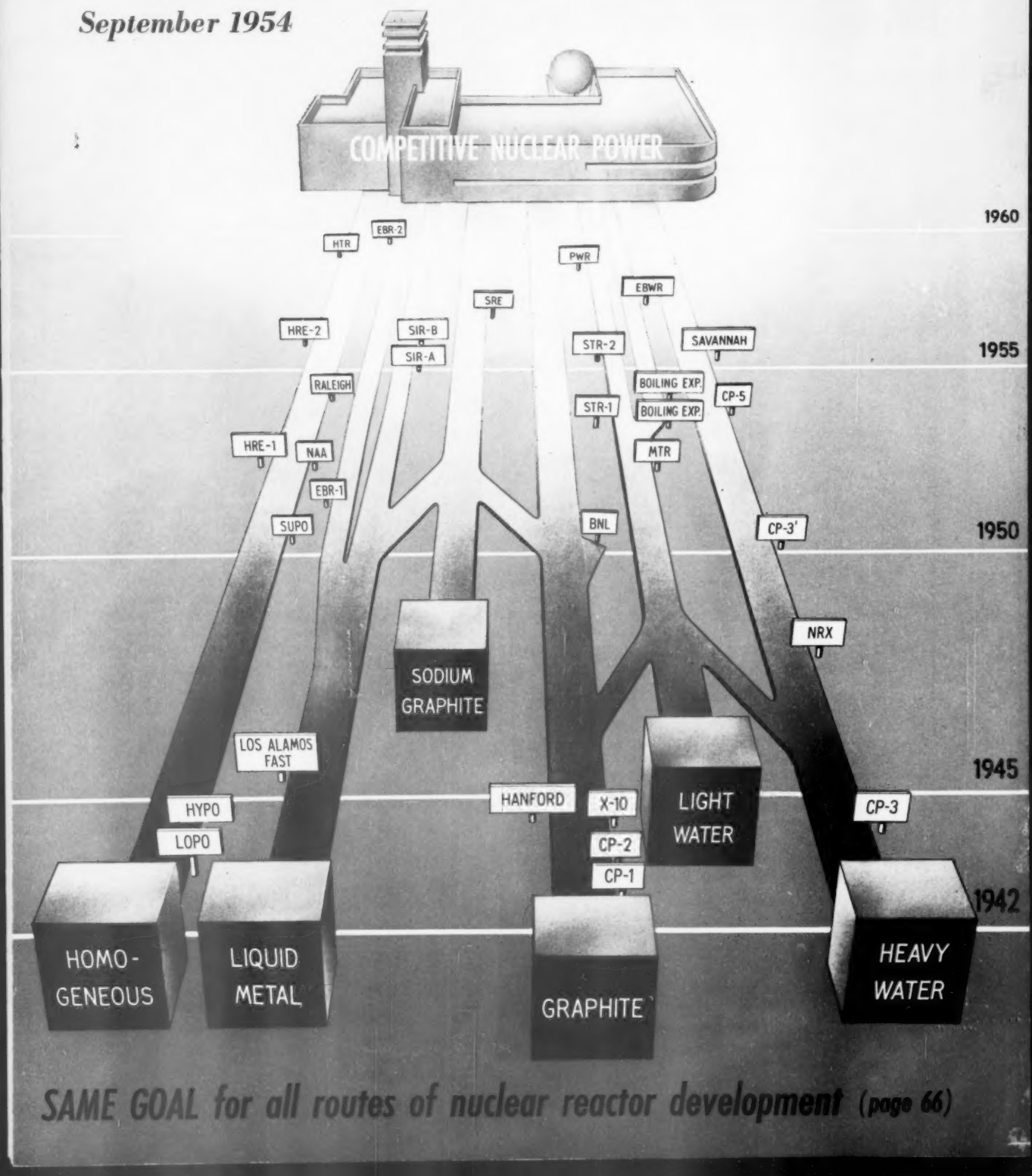
September 1954



SAME GOAL for all routes of nuclear reactor development (page 66)

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CEC Service Engineers quick change of ion analyzers (right) adds flexibility to Consolidated's two process monitoring mass-spectrometers. A cycloidal focusing analyzer assembly of the 21-620 type is being mounted in the vacuum rack in place of the Diatron analyzer of the 21-610.

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NUCLEONICS

SEPTEMBER • 1954

Vol. 12, No. 9

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Cross-section photo of a typical industrial expansion joint fabricated for a petroleum refinery. Welds were made with the shielded inert gas metal arc (SIGMA) process, including lap, fillet, edge and groove types, joining AISI type 321 stainless bellows and Schedule 285 type mild steel pipe ends.

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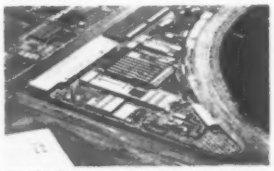

PLANTS. *In San Diego (Photo above) and Des Moines. A total of 1,400,900 sq. ft. floor space. Approximately 5,000 employees. Annual sales over $65,000,000.*

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Advances in Applied Radiation

DEVELOPMENTS in the FIELD OF APPLIED RADIATION ENERGY, its APPLICATIONS and the APPARATUS USED TO PRODUCE IT

Chemical Analysis by Neutron Activation

Samples made temporarily radioactive under neutron bombardment can be analyzed to detect minute quantities of impurities or trace components. In many cases, concentrations in the "parts-per-million" range can be measured.

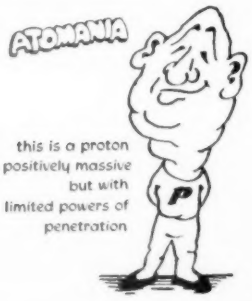
This technique has heretofore been restricted to laboratories having access to the intense neutron fluxes obtainable in nuclear-reacting piles. But today, with the availability of Van de Graaff particle accelerators, intense neutron fluxes can be produced in industrial laboratories as well as in academic research establishments. With HIGH VOLTAGE'S two-million-volt Model AK-N Van de Graaff, for example, thermal-neutron fluxes of 5×10^6 n/sec-cm^2 are routinely obtainable. Activation analysis can be performed on over 60 elements with detection sensitivities better than 100 parts per million, using this neutron source.

Already, industrial laboratories are actively engaged in exploring the possibilities of this new analytical method. Results are unambiguous and are usually obtained with little sample preparation and in a relatively short time. Full information concerning activation analysis is now available from HIGH VOLTAGE, including an exhaustive table of all isotopes susceptible to neutron bombardment. Write for "Activation Analysis with Van de Graaff Neutron Sources."

High-vacuum Plumbing

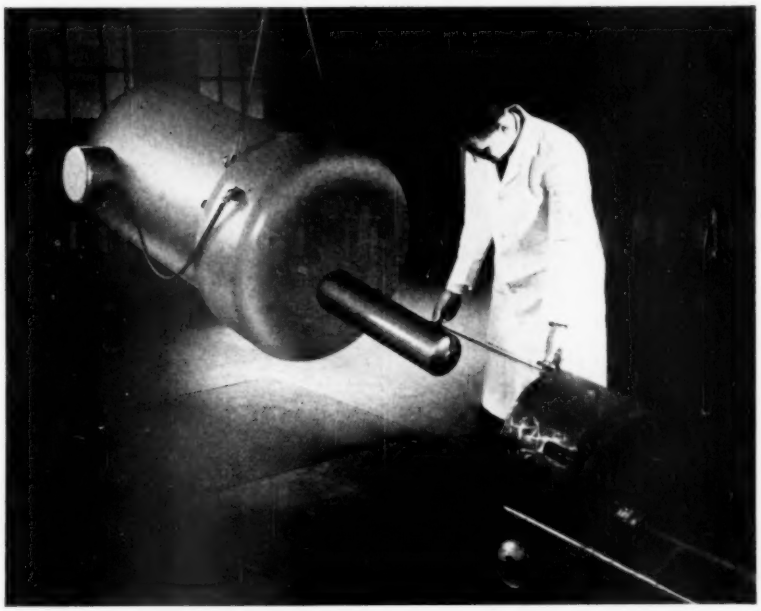
For some time, HIGH VOLTAGE has been concerned with the development of reliable, standardized high-vacuum components. The resulting design combines ruggedness with simplicity and flexibility and appears to have applications in many types of industrial and laboratory installations.

dependex high-vacuum plumbing is described in an eight-page bulletin available on request to HIGH VOLTAGE.



A New Low-cost Supervoltage X-ray Source

The need for a lower cost x-ray source for the precision inspection of steel thicknesses from 2 to 5 inches has long been felt. For many applications, radioactive sources use too much time and often leave something to be desired in definition or sharpness — and conventional x-ray machines lack sufficient penetrating power for the more difficult jobs. On the other hand, equipment for the production of highly penetrating x-rays at energies of one million volts or more has involved a capital expenditure which could be justified only for very heavy and specialized industrial operations.



At the recent meeting of the American Society for Testing Materials, HIGH VOLTAGE announced a new one-million-volt x-ray generator designed to fill the gap. Capable of penetrating steel thicknesses up to 5 inches in reasonable exposure times, this new unit, our Model JR Van de Graaff, is priced at $25,000 — less than half the cost of other available supervoltage equipment. One unique feature of the Van de Graaff for radiography is its small focal spot — the source of x-rays is less than 1 mm in diameter — making possible the production of radiographs with exceptionally clear detail.

The entire unit weighs less than 2,500 pounds and is about the size of a household refrigerator. It is therefore easily transported by crane or lift-truck. We believe that the availability of this x-ray source will be of major importance to the non-destructive testing techniques of heavy industry.

Columbia University

The 30-ton pressure vessel for Columbia University's 6-million-volt Van de Graaff accelerator has now been delivered to HIGH VOLTAGE. When completed in early 1955, this accelerator will be used for obtaining precise nuclear data by the university's Physics Department, under the direction of Prof. W. W. Havens. HIGH VOLTAGE is building this Van de Graaff, the third of its kind, under contract to the U.S. Atomic Energy Commission.

HIGH VOLTAGE ENGINEERING CORPORATION
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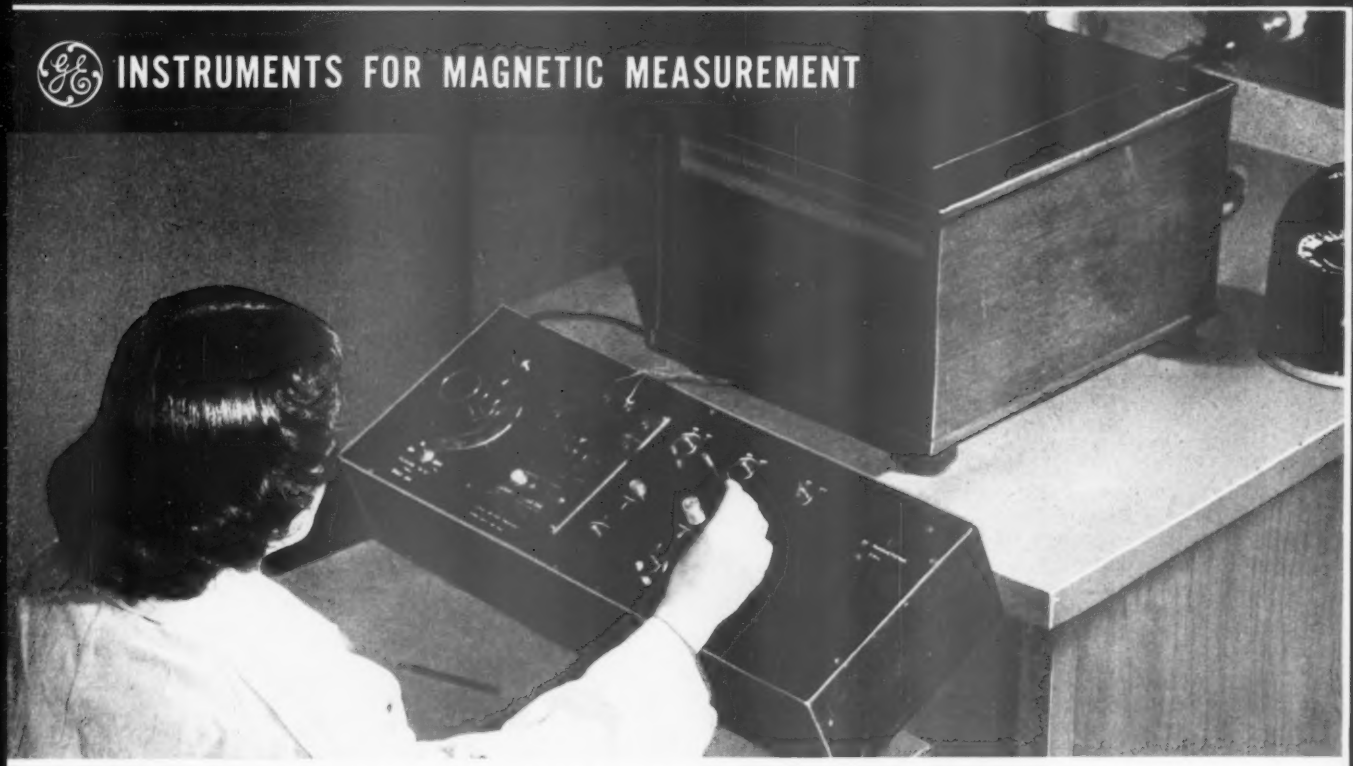
INSTRUMENTS FOR MAGNETIC MEASUREMENT



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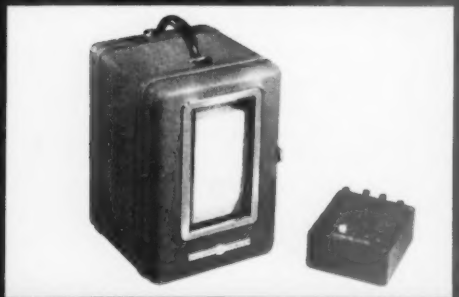
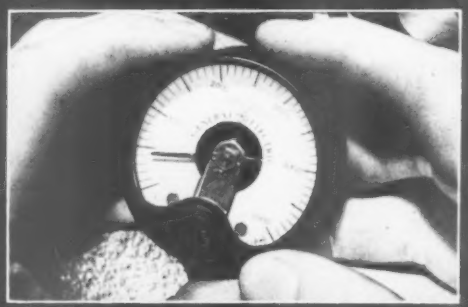


GAUSS METER



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GENERAL ELECTRIC

LATE NEWS and COMMENTARY

Effect of Law Change

With the Atomic Energy Act of 1954 enacted into law on Aug. 30, AEC has set a battery of experts and attorneys to work interpreting the law and determining how to implement it. It is expected to take at least six months before the complexities of such things as the licensing provisions will be worked out.

However, action is already being taken on one objective of the law—broadening access to classified information. Section 145f of the Act makes possible a new category of classified data—so-called "gray" area—access to which will not require *Q*-clearance. Instead, only *L*-clearance, quickly obtainable without full-fledged time-consuming FBI investigation, will be required. Because it is expected that much nuclear reactor data—particularly that concerned with things external to the reactor core—will be placed in this relatively nonsensitive category, industrial activity in the nuclear power field will be facilitated.

Work at AEC toward creation of gray area is going on in preparation for early October meeting in England with British and Canadians. Under tripartite declassification agreement, British and Canadians will have say on scope of gray area. Hope is that working agreement can be obtained and that gray area can be mapped out by year's end. AEC will follow up by fixing rules to govern domestic use of gray-area information.

•

Research Reactors

AEC has received about 10 inquiries from organizations interested in building small research reactors. About half of these are formal applications. The new law will ease AEC's job of doing business with such groups, but to what extent remains to be seen. Some things—such as fact that universities will be able to borrow larger quantities of fuel without need for a Government custodian in residence—are clear under the new law.

•

International Activities

One reason behind formation of European Atomic Energy Society (NU, July '54, p. 5) was to have formal body for possible dealings with U. S. on President's atomic pool proposal. Gunnar Randers, director of Dutch-Norwegian atomic project and executive vice president of new society, said last month: "Establishment of the 8-nation European Atomic Energy Society shows that Europe is ready to consider any proposal for cooperation with the United States on the peaceful use of nuclear energy, along the lines suggested by President Eisenhower and AEC Chairman Lewis L. Strauss." The group is tentatively planning an international conference in Rome next summer with "the most suitable type of reactor" as its chief topic of discussion.

Efforts are also being made in this country to set up the international nuclear conference proposed and sponsored by the President. NUCLEONICS has heard that AEC is going all out on soliciting papers for this conference from all Project laboratories. The meeting is tentatively scheduled for the first part of 1955, but it is reported that it may not actually be held until 1956, depending upon the willingness of other nations to participate and contribute.

•

Oak Ridge Reactor

Architect-engineering work on the new $2.8-million research reactor to be built at Oak Ridge National Laboratory by 1957 will be by subcontract under Union Carbide and Carbon Corp., operator of ORNL. The laboratory will furnish design criteria (see article on p. 36 for full design details), and will install reactor equipment. The construction contractor will be selected on a lump-sum bid basis.

LATE NEWS (Continued)

Isotope Prices The Joint Congressional Committee on Atomic Energy has recommended to AEC that it broaden its practice of charging cancer researchers 20% of "list" price for radioisotopes so that all medical isotope users would be included (see p. 79 for details). The JCAE also recommended that radioisotopes be furnished "as elements and in chemical compounds at less than cost for employment in selected other fields, such as biology." One factor working in favor of extension of such price breaks is AEC's conviction that they have resulted in an increase in cancer research work.

•

Australian Uranium South Australia's $11.2-million uranium mine and concentration plant at Radium Hill is due to begin full production next month, and the first exports of high-grade uranium oxide to Britain and the United States are expected to be shipped early next year.

•

PWR Ground was broken at Shippingport, Pa., on Sept. 6 for pressurized water reactor (PWR), nation's first civilian atomic power plant. Classified meeting on status of PWR was held in Pittsburgh on Aug. 27 for industrial representatives.

•

Copper, Brass Use AEC continues to be a major consumer of metals. In fiscal 1954, AEC used 4.5-million lb brass mill products (pure copper sheet, etc.); 13-million lb wire mill products (copper and copper-base alloys); and 860,000 lb foundry products including powder (copper and copper-base alloy). In addition, AEC has given priority assistance for obtaining 6.5-million lb brass mill products, 3.5-million lb wire mill products for related electric power uses (expansion of generating capacity).

•

Reactor Request World Steel Corp., Chicago, has requested authority from AEC to use a nuclear reactor in a proposed new steel plant in the Chicago area. Company is interested in boiling water reactor to serve 200–300,000 kw load.

•

Army Reactor Bids Competition for architect-engineering contract for Army "package" power reactor (APPR), first competitive-bid reactor in country, is fierce. Although bids to 33 companies (see Aug. NU, p. 56, for names) only went out at the end of August (reportedly delayed until then to await passage of new atomic law), strong evidence already exists that many companies are anxious to get this job. Bids are due Nov. 24.

The reactor will be built on a small peninsula in the Potomac River at Fort Belvoir, Va., less than 25 miles from Washington, D. C. Because of closeness to center of population, special safety precautions will be taken, including using a sealed building 29 ft wide, 42 ft high and 80 ft long.

Although the original Oak Ridge National Laboratory design of the reactor called for production of 1,250 electrical kw, this has been upped to 1,700 kw because plant will not be tapped for steam, thus permitting maximum electrical output. The reactor, however, will be adaptable for dual-purpose use. Thermal capacity of plant will be about 10 Mw.

Bidders have been provided with copies of the ORNL design. However, this is merely a guide. Companies have been given considerable flexibility on details of design. They will be required to guarantee a limited performance for the plant, including the fuel elements. The question of whether a subcontractor or AEC will supply the fuel elements is left for final negotiation.

NUCLEONICS SEPTEMBER, 1954

Jerome D. Luntz, *Editor*

A Challenge

THE THIRD PHASE in the development of atomic energy in this country began last month when the Atomic Energy Act of 1954 was enacted into law. The first phase was the totally secret military project during World War II. Phase two was a continuation of the 100% government-controlled activity with the civilian Atomic Energy Commission making major strides on pushing peacetime applications as a sideline to its military operations. Now we enter a new era with new legislation specifically designed to foster peacetime activities.

Although the law has been passed on the assumption that it's urgent for this nation to develop peacetime atomic energy, we think it's worth restating the reasons for this urgency.

First, what will the new law do? It will permit industry to build, own and operate power reactors, and to export them. The government will be able to give power reactor data and fissionable material to other nations. Much technical information will be placed in a relatively nonsensitive classification category which will be accessible to many (so-called "gray" area of classification). Many exclusive patents will be permitted (some will be subject to compulsory cross-licensing). Development of radioisotope applications will be fostered because of encouragement of industrial activity.

NOW, WHY PRESS peacetime activities? For the past decade, the U. S. has unquestionably had the most substantial atomic energy program in the world—measured in dollars and cents, if nothing else. Probably at least 90% of the roughly $12-billion that's been appropriated for the program has gone into military applications. In the minds of many, this has been instrumental in staving off a third world war.

It is thus not in the least surprising that, since atomic energy became a subject for public discussion in 1945, it has been a symbol of war. Now it is within our grasp to change this thinking—and not merely for the sake of doing so.

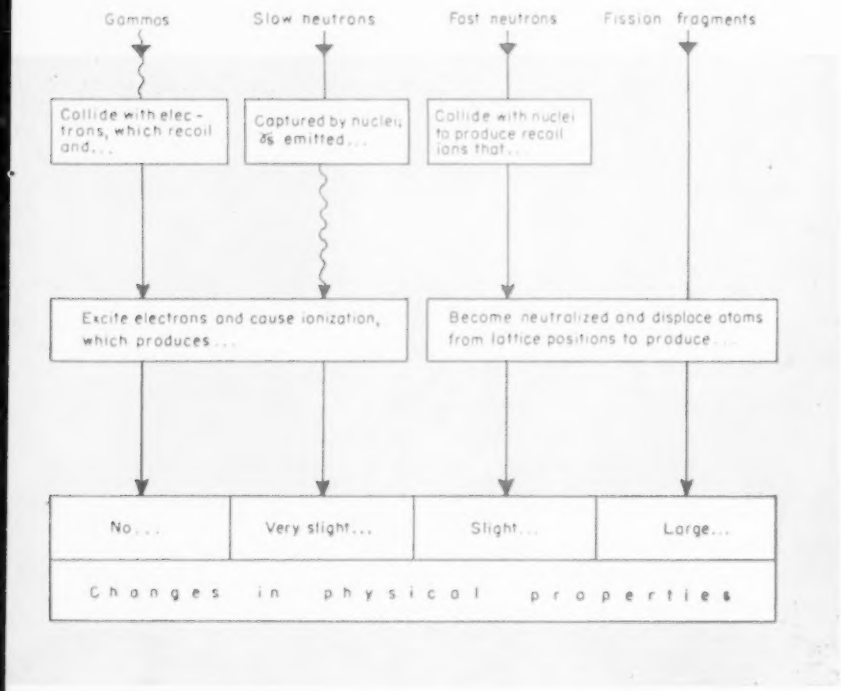
At home, the public is long overdue on reaping the peacetime benefits of the military effort. Although we have no urgent need for new low-cost sources of energy, early development of competitive nuclear power will not be an unwanted event. In fact, predictions have been made with good reason that in the coming years appreciable quantities of new power capacity will be nuclear rather than coal-produced.

In addition to power possibilities, industry can look forward in 10 years, according to AEC, to savings of $1-billion a year through use of radioisotopes.

Abroad, there is an immediate job this country can do. Many of the free nations are power-poor. Nuclear power plants that can be built today would be competitive in some of these countries. We can offer them technical information or our industry can sell them actual plants.

THE ATOMIC ENERGY ACT OF 1954 is aimed at permitting these domestic and international activities. But the mere passage of the act is no guarantee that these things will happen. Rather, a challenge has been flung at private industry by Congress. More than just having the *opportunity* of developing atomic energy applications, industry has the *responsibility* of doing so.

Radiation Effects on Reactor . . . METALS



By C. R. SUTTON and D. O. LEESER
Reactor Engineering Division
Argonne National Laboratory
Lemont, Illinois

TECHNICAL PROBLEMS faced by reactor-structure designers are based largely on the combined effects of high temperature and radiation on metals. Metals also are exposed to radiation when they are used in pressure vessels, closures, welds, valves, piping, pumps, gears, bearings, and other related reactor equipment.

Carbon steels, stainless steels, nonferrous metals, and cobalt and nickel alloys have been preliminarily tested to determine their suitability for service in radiation fields.

The diagram shows how the most damaging types of reactor radiation affect metals.

When fast particles strike a metal's nuclei, atoms are ejected from their lattice positions to cause displacements. These reactions affect conductivities, creep, hardness, and other properties. Many of the changes can be annealed out at high temperatures.

Radiation damage is somewhat analogous to cold work—with these important exceptions: 1, the mode of damage production is different; 2, radiation-induced hardening is not as large as cold-work hardening; 3, radiation affects an extremely microscopically localized region; and 4, radiation effects are nondirectional. In both processes, the effect is attributed to rearrangement of atoms within crystals and subsequent dislocations in the atomic lattice. Small percentages of such random disturbances can result in large changes in mechanical properties, the changes being proportional to the number of displaced atoms.

In general, recoil ions (even neutralized ones) lose most of their energy by ionization. Only a small fraction is dissipated by momentum losses. Thus, damage to metallic (and ionic) solids by displacement of atoms occurs at considerably higher radiation doses and on a much smaller scale than damage to organics by ionization. Since metals and ionic compounds are affected very little by ionization, these materials are considerably more resistant to radiation damage than are covalent compounds such as organics.

TEST PROCEDURES, RESULTS

The amount of radiation to which a specimen was exposed is expressed in *nvt* ("integrated dose"). This is the number of neutrons incident on a square centimeter for the total time that the specimen is exposed. Slow neutrons have energies of about $^1/_{40}$ ev. Fast neutrons have energies at least greater than 1 Mev.

Control specimens were held in media and ambient temperatures similar to those of the irradiated specimens. This permits a separation of variables within the limits of the experiment. Remotely-controlled equipment tested irradiated specimens.

Hardness

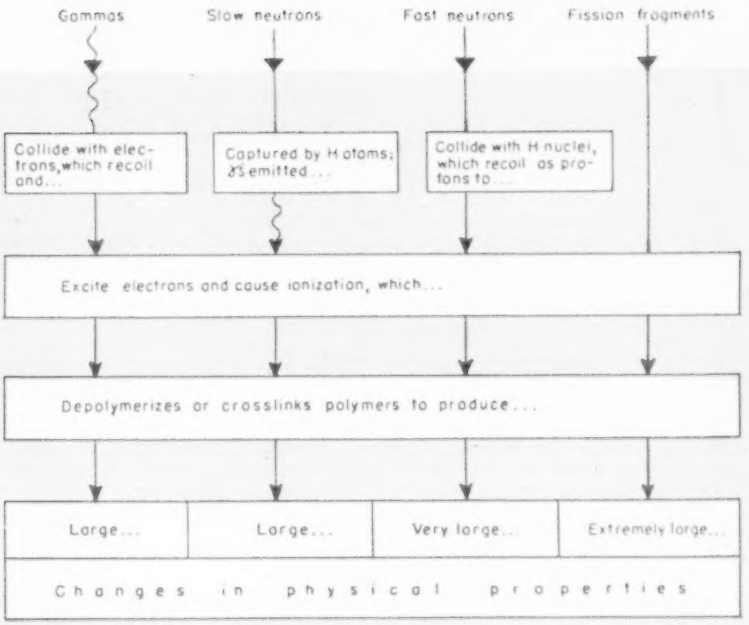
Tests described in Table 1 indicate that hardening: 1, is greater for softer metals than for those already hardened; 2, is not a direct function of carbon content; 3, is preserved at room temperatures (but changes are lessened at

(Continued on page 13)

Materials

. . . NONMETALS

By V. P. CALKINS
Aircraft Nuclear Propulsion Department
General Electric Company
Cincinnati, Ohio



FROM THE DESIGNER'S VIEWPOINT, one broad aspect of the radiation damage problem is of considerable concern—what materials can be used in a reactor and what is their useful life? Radiation will change the properties of practically any material to some degree. The amount of change is a function of the material's nature and chemical configuration, the particular property being measured, and the type and amount of radiation. But experimental data indicate that certain generalizations can be made concerning threshold doses for various types of materials. An understanding of damage mechanisms and dose units permits valid application of the generalizations.

Mechanism of Damage

The diagram shows how the most damaging types of reactor radiation affect organic materials. Ionic compounds (high-melting salts and oxides) are damaged by the same mechanisms as metals, but some of the electrons freed by fast neutrons are trapped in lattice imperfections and form "F" centers to discolor such materials as viewing glass. Heat or light anneal the coloration.

Because fission fragments have short ranges, they will only damage materials in contact with the fuel. In a reactor, slow-neutron-induced damage can equal that from gammas. Gammas from neutron-capture reactions with certain metals will cause increased damage when organics are in contact with such metals.

A given number of gammas causes considerably less damage to organics than an equal number of fast neutrons of the same energy. The probability of gammas colliding with electrons of the organic atoms is not as great as the probability of fast neutrons colliding with nuclei of the hydrogen atoms.

When a large volume of organic material is present, the intensity of the 2.17-Mev gammas resulting from slow-neutron capture by hydrogen can be about as high as the reactor's gamma flux—and equivalent damage can result.

With chloro-organics such as neoprene, the (n,γ) reaction produces considerable damage because of chlorine's high slow-neutron absorption cross section. If nitrogenous organic compounds are exposed to thermal neutrons, damage results from ionization caused by the proton from the N^{14} (n,p) C^{14} reaction. If the material's nitrogen content is high, a major part of the damage produced by slow neutrons might be due to this reaction.

For organic or other covalent hydrogeneous materials containing lithium or boron, the primary damage results from dense ionization caused by alpha particles given off after capture of slow neutrons by either Li or B. These alphas cause considerable damage.

Radiation units. Damage suffered by any material as a result of exposure to radiation should be a function of the actual energy absorbed or deposited per unit mass of material. Since γ-rays, X-rays, electrons, β-rays, and slow neutrons produce damage by the same mechanism, equivalent damage to the material should result for the same energy deposition. Fast neutrons, protons, α-rays and fission products produce damage by other mechanisms—thus a different damage vs energy relationship might be expected.*

Type and amount of damage a given material will suffer under any reactor's radiation conditions can be predicted with a fair degree of certainty if the radiation damage of various classes of compounds as a function of absorbed energy can be established on a sound experimental basis. Such work is in

* Alpha-ray bombardment of water produces considerably higher concentrations of hydrogen and hydrogen peroxide than X-ray or electron bombardment produce (*1*). Highly concentrated amounts of hydrogen and hydroxyl radicals are produced along the tracks of the heavily-ionizing α-particles, whereas X-rays and electrons cause these radicals to be produced more uniformly throughout the water system. The higher concentration of radicals permits more of the like radicals to combine to form H_2O_2 and H_2.

On an equivalent energy basis, irradiation by α-rays produces more H_2 and H_2O_2 than irradiation by a combined reactor flux of fast and slow neutrons, and γ-rays.

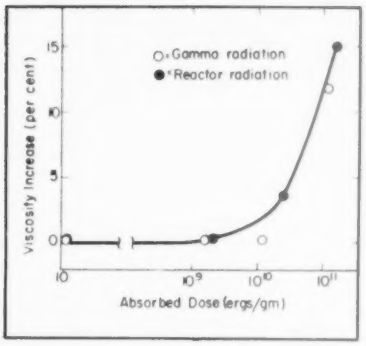


FIG. 1. Change in toluene's viscosity as a function of absorbed energy. Common curve shows equivalency of damage for equal energy deposition

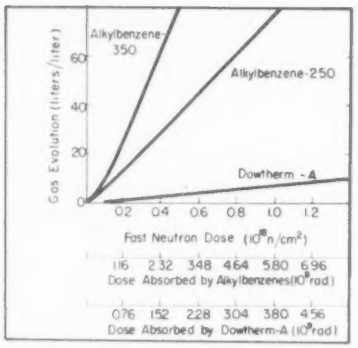


FIG. 2. Gas evolved *in situ* from alkylbenzenes 250 and 350, and Dowtherm-A as functions of absorbed dose and the fast-neutron component of the reactor flux (ratio ≈ 1 fast neutron : 2.1 slow neutrons : 2.3 γ). T = 300° F

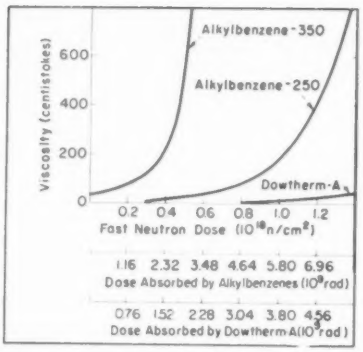


FIG. 3. Viscosity (at 100° F) of alkylbenzenes 250 and 350 and Dowtherm-A plotted as functions of absorbed dose and the fast-neutron component of the reactor flux (ratio same as in Fig. 2). Temp. during irradiation was 300° F

progress, but the relationship has not been firmly established as yet.

Preliminary results indicate that gamma rays and reactor radiation can produce equivalent damage by different mechanisms. Change in viscosity as a function of gamma and reactor radiation in terms of calculated energy absorption is shown in Fig. 1 for samples of toluene irradiated in a pure gamma source and in a graphite reactor. The common curve shows that equivalent damage was incurred for equivalent energy deposition. At higher energy-absorption levels, this direct relationship might not be valid.

Since radiation damage is proportional to energy deposition, a unit of energy deposition is needed. The original units for measuring radiation—the roentgen, rep, and rem—measure the effect of radiation on animal tissue, but they are inadequate for radiation damage studies of inanimate materials.

A general unit of energy deposition that applies to either animal tissue or inanimate material has been formulated (*2*). *Intensity* of radiation is the energy flowing through a unit area per unit time (erg/cm²/sec or watt/cm²). *Quantity* of radiation is the total energy passed through a unit area (erg/cm² or watt-sec/cm²). The actual amount of this energy *absorbed* per unit mass of any given material is measured by the "rad" (1 rad = 100 erg/gm).

Component Service Life

Analysis of data such as that shown in Figs. 2–6 permits making broad generalizations regarding the estimated service life of various components of a typical nuclear power plant. For this purpose, a nuclear power plant can be visualized as consisting of three major systems: 1, reactor and shield; 2, controls and instruments; 3, heat engine.

Typical components of each of these major systems are listed in Tables 1 and 2. Threshold damage values or service lives are given as the radiation dosages estimated to cause a 25% change in one or more physical and chemical properties affecting the general usefulness of a material. Dosage values are used since radiation damage is essentially a function of total radiation received rather than of radiation intensity.

Since a considerable portion of the

TABLE 1 Radiation Damage to Reactor and Shield Components

Components	*Type of Damage*	*Threshold* (rad)*
Water	Gas evolution, corrosion	∞
Hydrocarbons		
Paraffins and olefins	Gas evolution, polymerization	1×10^8
Mono-phenyls	Gas evolution, polymerization	3×10^8
Di- and poly-phenyls	Gas evolution, polymerization	1.5×10^9

*For 25% damage. 10^8 rad = 10^{19} ergs/gm = 1,000 watt-sec/gm = 430 Btu/lb ≈ 3×10^{17} slow neutrons/cm² + 3×10^{16} fast neutrons/cm² (>0.7 Mev) + 1.5×10^{17} γ/cm² (E_{avg} ≈ 1 Mev).

TABLE 2 Radiation Damage to Control, Instrument and Heat Engine Components

Components	*Susceptible Material*	*Threshold* (rad)*
Capacitors	Organics: Paper or oil dielectric and Bakelite or waxed paper cover	$4.5–7.0 \times 10^6$
Resistors	Plastics: Bakelite cover for resistance	
Microswitches	Plastics: Plastic case and actuator	
Selsyns	Electrical insulators (organics)	
	Wire insulation, brush holder, slot liners, end punchings and casing insulation	
Electric motors, wiring	Electrical insulators (organics)	
Gaskets, seals	Elastomers, leather	
Hoses, couplings	Rubber, plastic hoses; plastic, fabric couplings	
Fuels, lubricants, hydraulic fluid	Petroleum base (paraffinic hydrocarbons)	$1.0–2.5 \times 10^8$

*For 25% damage. $4.5–7.0 \times 10^6$ rad ≈ 10^{15} slow neutrons/cm² + 10^{15} fast neutrons/cm² (>0.7 Mev) + 5×10^{15} γ/cm² (E_{avg} ≈ 1.0 Mev). $1.0–2.5 \times 10^8$ rad ≈ 3×10^{17} slow neutrons/cm² + 3×10^{16} fast neutrons/cm² + 1.5×10^{17} γ/cm².

Calculating Energy Absorbed

Precise calculations of radiation absorbed by a material can become complex and laborious, but approximations produce very useful results.

From fast neutrons. The amount of fast-neutron energy absorbed by an organic compound depends on dose and on the scattering cross section of hydrogen, which in turn is a function of neutron energy. Thus, although fast-neutron intensities are commonly expressed as neutrons of 0.5–1.0 Mev or higher, considerable damage will result from neutrons of a much lower energy range. Approximately 40–50% of the energy absorbed by an organic compound from fast neutrons in a graphite pile will come from neutrons with energies of 0.01–0.5 Mev; and more than half the energy will come from neutrons with energies of 0.5–1.0 Mev. This is the case because: 1, pile fluxes of neutrons of lower energy are numerically greater than the fluxes of neutrons of higher energy; and 2, the scattering cross section for hydrogen increases from 4.5 barns at 1.0 Mev to approximately 20 barns at 0.01 Mev. In a water-cooled pile, the contribution from 0.01–0.5-Mev neutrons might be only 10% of the total energy deposited by all the fast neutrons.

The amount of energy absorbed per gram of an organic material from a fast-neutron dose ϕ_n with an average energy E_n is $E_g = \phi_n \Sigma_s E_n / \rho e$, where Σ_s is the macroscopic scattering cross section of H in the material considered.

Total fast-neutron energy absorbed is calculated by adding the energies absorbed from neutrons of each small energy range (using the dose and scattering cross section corresponding to each energy range). The fast-neutron energy absorbed at 300° F by alkylbenzene is calculated to be 2.2×10^9 rad at a fast-neutron dose of 10^{18} n/cm²; of this, 0.2×10^9 rad is from neutrons with energies less than 0.5 Mev (particularly from those between 0.01–0.5 Mev), and 2.0×10^9 rad from neutrons $\geqq 0.5$ Mev.

From gammas. Energy absorbed (per gram of material) from gamma radiation can be approximated by $E_g = \phi_\gamma \mu_\gamma E_\gamma$, where μ_γ is the energy absorption coefficient (cm²/gm) of the material for gammas of energy E_γ. The energy absorption coefficient is obtained by multiplying the probability of each interaction process by the probable fraction of the photon energy actually dissipated in the absorber as a result of the process.

Alkylbenzene's μ_γ will not differ markedly from that for water. Using μ_γ for water from ref. (5), a gamma dose of 2.3×10^{18} γ cm² and an average photon energy of 2.0 Mev, $E_g = 1.19 \times 10^{17}$ Mev/gm $= 1.9 \times 10^9$ rad.

From thermal neutrons. For the (n,γ) reaction, energy absorbed per gram can be approximated by $E_g = \phi_n \Sigma_a E / \rho$, where E is the average energy of the photons generated by the (n,γ) reaction. For alkylbenzene at 300° F and a thermal neutron dose of 2.1×10^{18} n/cm², $E_g = 1.68 \times 10^9$ rad.

Combined absorption energy. Total energy absorbed per gram by alkylbenzene at 300° F from an integrated reactor flux of 1.0×10^{18} fast neutrons/cm² ($E_n \geqq 0.5$ Mev) plus 2.3×10^{18} γ/cm² ($E = 2.0$ Mev) plus 2.1×10^{18} slow neutrons/cm² is $(2.2 + 1.90 + 1.68)10^9 = 5.8 \times 10^9$ rad.

For Dowtherm-A, energy from both the fast and slow neutrons will be less under identical dosage conditions because of Dowtherm-A's lower hydrogen content. Since its hydrogen content is approximately 60% that of alkylbenzene, the energy that Dowtherm-A absorbs from fast neutrons is

$$E_g = 2.2 \times 10^9 \left(\frac{3.4}{6.0}\right)\left(\frac{0.86}{1.00}\right) = 1.1 \times 10^9 \text{ rad}$$

and from slow neutrons

$$E_g = 1.68 \times 10^9 \left(\frac{3.4}{6.0}\right)\left(\frac{0.86}{1.00}\right) = 0.84 \times 10^9 \text{ rad}$$

where 6.0 is the number of hydrogen atoms per cm³ of alkylbenzene times 10^{-22}, and 3.4 is the same quantity for Dowtherm-A; 0.86 is the density of alkylbenzene at 300° F, and 1.00 is the same quantity for Dowtherm-A.

The gamma energy contribution to Dowtherm-A is approximately the same as for alkylbenzene.

The formula used for calculating fast-neutron energy deposition in organics is applicable to small samples as well as large samples. Formulas used for calculating slow-neutron and gamma-ray energy deposition apply, with fair accuracy, to moderately large samples of organics immersed in a sea of like material, i.e., where no sharp boundaries exist. These conditions were met for the tests conducted on the alkylbenzenes and Dowtherm-A since 600-cm³ samples were irradiated in aluminum containers in a water-cooled reactor.

However, the formulas used for slow-neutron and gamma-ray deposition do not apply very well to small samples of organics tested in a dissimilar environment such as a graphite reactor. Many of the thermal neutrons are not captured at all. And those captured lead to generation of gamma rays, most of which readily escape from the test system. Similarly, the energy deposited by gamma rays will be a smaller fraction than that deposited in large samples where no sharp boundaries exist. Therefore, the total energy absorption in small organic samples in a graphite reactor will be appreciably less than in large organic samples in a water-cooled reactor (for equivalent dosages and energy spectra).

For small samples (100 cm³ or less) of the usual organic materials in a graphite reactor, this decrease in energy deposition by thermal neutrons varies from 90–98%, and the decrease in energy deposition by thermal neutrons varies from 70–75%. This decreased energy deposition is reflected in the doses used in Figs. 5, 6, and 7 and in Tables 1, 2, and 3. These doses are based on the calculated value that approximately 65% of the total energy deposited will be due to fast neutrons and 35% will be due to a combined energy deposition by gammas (25–30%) and slow neutrons (2–10%). This agrees with calorimetric results obtained with the ORNL graphite pile (4). Use of this corrected dose:radiation relationship is justified on the basis that most of the materials shown here were tested as small samples comparable in size to reactor components.

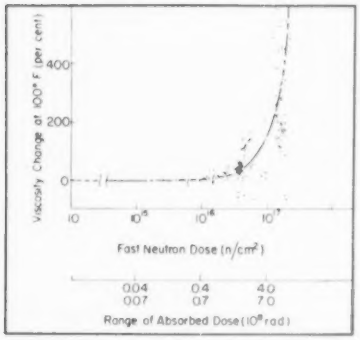


FIG. 4. Composite viscosity change in 24 organic liquids plotted as functions of rad dosage range and the fast-neutron component of the reactor flux (ratio ≈ 1 fast neutron : 10 slow neutrons : 5 γ). All liquid hydrocarbons polymerize. Viscosity changes by 25% just prior to the exponential increase, thus the radiation dosage for 25% viscosity change can be considered as the limit for engineering applications

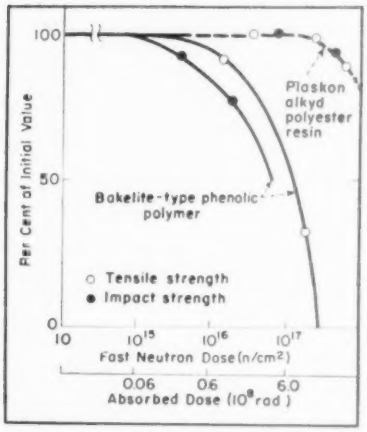


FIG. 5. Tensile and impact strength changes of two typical plastics (often used as insulation) plotted as functions of absorbed dose and the fast-neutron component of the reactor flux (ratio same as in Fig. 4). Many plastics are less resistant (3)

reactor and shield will be metallic, they will not be very susceptible to radiation damage. Some materials, such as water and liquid organics (Table 1), are of considerable interest as moderators, coolants, and shielding compounds because of their high hydrogen contents.

Water is much more radiation-resistant than the organics. Although water does suffer radiation decomposition, an equilibrium pressure is attained—whereas nonequilibrium pressures result from decomposition of organics. However, the gas formed from the organics frequently can be bled off readily by judicious design of the liquid system. With the use of the proper container materials, corrosion does not present a problem in either case; but special care should be exercised, particularly for the organics, to avoid container materials susceptible to hydrogen embrittlement.

Thermocouples that are integral portions of control and instrument systems are subject to a particular type of radiation damage. Being almost invariably metallic in nature, they are quite resistant to radiation-induced changes in physical and chemical properties, but reactor radiation will produce heat in metallic samples. Since thermocouples are used to measure temperature, the radiation-induced heat can cause false readings. Allowance must be made for this excess heat, and calibrations of the thermocouples should be made in a radiation field and under flow and temperature conditions similar to those anticipated in use.

Methods to Increase Life

Tables 1 and 2 show that the susceptibility of power-plant components to radiation damage is a function of the covalent nature of the component materials. The most effective method to improve radiation damage threshold of such components is to replace covalent or organic compounds wherever possible with more radiation-resistant materials such as inorganic and ionic compounds (metals, salts, and certain ceramics) as shown in Table 3.

Polyphenyl-type compounds are among the best wherever a free-flowing oil is desired. Solid lubricants such as molybdenum disulfide and graphite are quite radiation resistant.

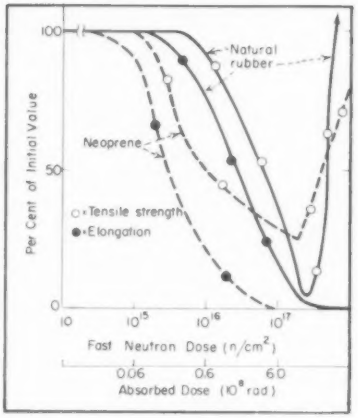


FIG. 6. Tensile strength and elongation changes in typical elastomers plotted as functions of absorbed dose and the fast-neutron component of the reactor flux (ratio same as in Fig. 4). Elongation changes for thiokol, GR-150, Silastic 7-170, and Hicar OR-15 show a 25% decrease at about 6×10^6 rad. Except for GR-150, these same plastics show a 25% change in tensile strength at about 6×10^7 rad; GR-150 has a 25%-threshold value of 6.5×10^6 rad (4)

* * *

The following personnel of the materials research and radiation studies groups of the General Electric aircraft nuclear propulsion department conducted most of the experimental work: Z. L. Ardary, D. E. Barnett, C. G. Collins, Jr., E. S. Collins, R. C. Fries, E. S. Funston, M. S. Grim, A. L. Grunewald, R. F. Hausman, R. A. Joseph, J. A. McGurty, G. W. Pomeray, L. E. Stanford, W. J. Stapp, T. V. Sparrow, C. C. Thomas, Jr., and R. C. Waldrop.

Mrs. V. L. Baker, H. S. Edwards, R. C. Fries, A. L. Grunewald, and G. W. Pomeroy assisted in preparing this article.

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TABLE 3—How to Improve the Radiation Damage Threshold

To improve	*Use*	*Increase in service life*
Reactor, shield	Mixtures of phenyl and polyphenyl compounds	Fivefold
	Di- and polyphenyl compounds	Tenfold
	Ionic or metallic solids	Thousandfold
Controls, instruments	Inorganic (ionic) compounds rather than organic*	Thousandfold
Heat engine	Antioxidant additives (to paraffins)	Threefold
	Polyphenyl-type lubricants	Tenfold
	Metallic gaskets and seals	Thousandfold
	Metallic hoses and couplings	Thousandfold

* Examples: mica and ceramic capacitors, ceramic-bodied microswitches and ionic insulation for selsyns.

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Radiation Effects . . .

Metals

(*Continued from page 8*)

high ambient temperatures); and 4, proceeds at a decreasing rate and probably approaches a saturation limit well below the fully-embrittled condition.

Chromium plating (0.005 in. thick) was applied to all surfaces of Nickel-A. After being irradiated under flowing 540° F water for 3×10^{19} nvt slow, surface hardness increases ranged from 0 to 6 points (Rockwell 45-T scale).

Two titanium specimens increased 1 point in hardness from Rockwell A-62–

TABLE 1—Radiation's Effect on Hardness of Metals

Material	nvt (10^{19} n/cm²) Slow	Fast	Temp. (°F)	Rockwell hardness Scale	Before	After
PLAIN-CARBON STEELS						
SAE-1018						
Annealed	1	—	450–500	C	6–7	8–10
Annealed	1	—	450–500	B	81–83	85–87
Hardened	1	—	450–500	C	20–25	22–25
Annealed	2	0.7	70–140	B	76–78	84–85
Hardened	2	0.7	70–140	C	22	23
SAE-1042						
Annealed	1	—	450–500	C	14	15
Annealed	1	—	450–500	C	21–23	27–29
Hardened	1	—	450–500	C	45–46	46–48
Annealed	2	0.7	70–140	C	18–21	9–10*
Hardened	2	0.7	70–140	C	40–45	45–46
SAE-1045						
Annealed	30	10	70–80	B	89–91	86–91
Hardened	30	10	70–80	C	52	37–43†
SAE-1095						
Annealed	1	—	450–500	C	31–32	33
Hardened	1	—	450–500	C	53–55	54–55
Annealed	2	0.7	70–140	C	29–32	33–34
Hardened	2	0.7	70–140	C	53–54	53–54
SAE-1113						
Annealed	1	—	450–500	C	12	16–18
Hardened	1	—	450–500	C	9–13	11–13
SAE-1141						
Annealed	1	—	450–500	C	12–20	25–26
Hardened	1	—	450–500	C	45	45–47
STAINLESS STEELS						
304						
Annealed	1.2	—	400–500‡	B	72–76	72–76
Malcomized	37	51	70–80	15N	89–91	93–95
309						
Annealed	1.2	—	400–500‡	B	81–83	81–85
316						
Annealed	37	51	70–80	B	82–83	98
Annealed	1.2	—	400–500‡	B	78–80	75–79
Cold-worked	37	51	70–80	C	25–27	28–32
329						
Annealed	3	—	540‡	A	50–53	50–54
347						
Annealed	3	—	540‡	B	89–90	81–90
Malcomized	1	—	—	15N	89–92	87–91
Annealed	1.2	—	400–500‡	B	81–83	81–83
TS-347A						
Annealed	3	—	540‡	A	50	54–55
Shot-peened	3	—	540‡	A	49–51	52–54
410						
Malcomized	37	51	70–80	15N	90–91	90–94
Malcomized	1	—	—	A	81–83	82–83
Malcomized	5	4	—	15N	91–92	92
431						
Annealed	3	—	540‡	A	64–65	68
Hardened	3	—	540‡	A	70–71	72
440C						
Hardened	5	4	—	A	75	77–79
Hardened	37	51	70–80	C	54–55	53–55
Hardened	5	4	—	C	56–57	58–59
Malcomized	1	—	—	15N	88–89	85–96
442						
Annealed	3	—	540‡	A	53–57	59–61
446						
Hardened	3	—	540‡	A	57	61–63
USS "W"						
Hardened	37	51	70–80	C	48–49	47–49
Hardened	3		540‡	A	73	74
Armco 17-4 PH						
Annealed	4.4	—	540‡	C	33–35	48–52
Hardened	4.4	—	540‡	C	50–51	45–50
Hardened	3	—	540‡	A	73	74
Armco 17-7 PH						
Hardened	4.4	—	540‡	C	43–44	44–48
Hardened	3	—	540‡	A	73	75
Malcomized	3	—	540‡	15N	92	95
NICKEL AND ITS ALLOYS						
Nickel-A						
	1	—	400–500‡	F	64–78	82–91
Hastelloy-C						
Cast	4	5	—	A	60–61	69–70
Cast	4	5	—	A	57–58	60–61
Wrought	1	—	400–500‡	C	25	30
Wrought	5	4	70–140	B	94–96	92–95
Wrought	4	—	540‡	C	24–27	27–30
Monel						
	5	4	70–140	B	81	95
	4	—	540‡	B	82–84	86–91
K-Monel						
	5	4	70–140	C	26	30
	4	—	540‡	C	24–28	25–28
Annealed	3	—	540‡	A	49–50	53–56
Hardened	3	—	540‡	A	68–69	69
Inconel						
	5	4	70–140	B	88	100
	4	—	540‡	B	89–90	93–102
Inconel-X						
	5	4	70–140	B	95	104
	4	—	540‡	B	94–99	99–104
COBALT-BASE ALLOYS						
Stellite-3						
	4	5	—	C	52	53–55
	4	5	—	C	45	49–51
	3	—	540‡	A	75–76	78–79
Haynes-25						
	3	—	540‡	A	61–62	62–63

* Decrease is unexplained. † Decrease due to corrosion products caused by leaking container. ‡ In flowing water.

TABLE 2—Radiation's Effect on Tensile Properties of Metals

Material	nvt (10^{19} n/cm²) Slow	nvt (10^{19} n/cm²) Fast	Temp. (°F)	Ultimate tensile strength (10^3 lb/in.²)	Yield strength (10^3 lb/in.²)	Elongation (%)
STAINLESS STEELS						
304*						
Annealed	0	0	400–500	92.5	44.0	70.8
Annealed	1	—	400–500	92.0	43.5	58.5
Annealed	1	—	400–500	95.5	48.5	41.0
309*						
Annealed	0	0	400–500	95.0	38.5	54.0
Annealed	1	—	400–500	99.0	43.5	51.0
316						
Annealed*	0	0	400–500	90.0	35.0	70.0
Annealed*	1	—	400–500	89.5	36.5	66.5
Annealed	0	0	70–80	79.5	—	—
Annealed	37	51	70–80	151.0	—	—
347*						
Annealed	0	0	400–500	99.0	37.5	56.6
Annealed	1	—	400–500	103.0	42.5	54.5
410						
Malcomized	0	0	—	69.0	47.0	—
Malcomized	4	5	—	70.0	62.0	—
Malcomized	0	0	—	70.0	44.0	—
Malcomized	4	5	—	75.0	61.0	—
440C						
Hardened	0	0	—	199.0	185.0	—
Hardened	4	5	—	240.0	205.0	—
Hardened	0	0	—	211.0	185.0	—
Hardened	4	5	—	240.0	200.0	—
USS "W"						
Annealed	0	0	70–80	113.0	—	—
Annealed	37	51	70–80	134.5	—	—
NICKEL ALLOYS*						
Nickel-A						
	0	0	400–500†	67.5	22.0	44.8
	1	—	400–500†	69.5	27.0	34.6
	1	—	400–500†	69.5	28.0	33.5
Hastelloy-C						
	0	0	400–500†	139.5	61.0	53.5
	1	—	400–500†	142.0	62.5	42.0
HIGH-DENSITY MATERIALS						
Tungsten						
	0	0	—	145.5	—	0
	0	0	—	160.0	—	0
	1	5	—	132.0‡	—	0
	1	5	—	102.0‡	—	0
Tantalum						
	0	0	—	72.0	—	19
	0	0	—	65.0	—	23
	1	5	—	88.0	—	17
	1	5	—	85.0	—	17
Tantalloy						
	0	0	—	136.0	—	29
	1	5	—	167.0	—	14
	1	5	—	163.5	—	14
Tantung-G						
	0	0	—	72.5	—	5
	1	5	—	68.5	—	4

* Reported by ORNL Metallurgy Division. † In flowing water. ‡ Decrease can be attributed partly to difficulty of aligning brittle specimens by remote control.

63 to 63–64 after 3×10^{19} nvt slow in flowing 540° F water; two other initially-softer titanium specimens, Rockwell A-57, increased 4 points.

Tungsten and tantalum-tungsten alloy changed hardness to only an insignificant extent after 10^{19} nvt slow and 5×10^{19} fast. Tantalum hardness increased 8 points to Rockwell A-57.

Tensile Strength

Data in Table 2 indicate that high ambient temperature tends to anneal radiation-damage's tensile-strength effects. Yield and ultimate strengths increased slightly and ductility decreased slightly. Differences in elastic modulus were within experimental accuracy. The increase in strength is related to the original hardness of the material rather than to the chemical analysis or method of hardening.

Ultimate tensile strengths of tungsten, tantalum, and tantalum-tungsten alloys increased 20–25%. Ductility did not change for tungsten but decreased 20% and 50%, respectively, for tantalum and the tantalum-tungsten alloy.

Hastelloy-C was affected more by temperature aging than by radiation. Radiation's effects on Monel, K-Monel, Inconel, and Inconel-X probably were reduced somewhat by the annealing effects of the 540° F operating temperature.

Nickel-A and Hastelloy-C undergo slight increases in yield and ultimate strengths and slight decreases in ductility when irradiated at 500° F. Comparison of the results of this irradiation with those at lower temperature (Table 3) indicates that radiation damage was annealed by the higher ambient temperature. Changes in modulus of elasticity were within experimental error.

Table 3 shows that the tensile strengths of five nickel alloys irradiated at 70–140° F increased 3–13% for unnotched specimens, and 6–11% for notched specimens. Except for Inconel, ductility decreased appreciably.

Stellite-3 showed unappreciable change after being irradiated. Test results were scattered (86,000 and 94,000 lb/in.²—irradiated; 104,000 lb/in.² and failure in grips—unirradiated), probably due to alignment difficulties with the brittle specimens.

Impact Strength

ASME types SA-70 and SA-212 mild-carbon boiler steels have similar chemical compositions. Table 4 shows that radiation affected both of them similarly. Ductile-brittle transition temperature increased and maximum-energy fracture (maximum impact strength) values decreased. Under ductile conditions, changes were greater for specimens exposed to high flux and low temperature than for those exposed to low flux and high temperature. These effects were not as pronounced

on the aluminum-killed material, probably due to the smaller grain size imparted by the added aluminum. Fine-grain size tends to promote lower transition temperatures, other things being equal.*

Fatigue Strength

Fatigue strengths of stainless-steel type 304, Grade I crystal-bar zirconium, and double-melted 2½% tin-zirconium alloy were unaffected by 10^{20} nvt slow and 10^{19} nvt fast at 140° F and 540° F.

Density, Dimensions

Nine structural metals were irradiated at 70–140° F for 4×10^{20} nvt slow and 3.5×10^{20} nvt fast. The metals (and average percentage density changes) were: Stellite-3 (+0.06), Stellite-6 (+0.11), Monel (−0.05), Nickel-A (−0.07), SA-212 plain-carbon steel (0), and stainless steel types 316 (−0.06), 347 (−0.09), 347 + Ta (−0.04), and 410 (−0.05).

Carboloy grades 44A, 883, 905, 907, and 999, tungsten carbides and tantalum carbides with cobalt binder were irradiated for 4×10^{19} nvt slow and 8×10^{19} nvt fast. Some dimensional changes were above probable experimental error; densities decreased 0.3–0.6% without any correlation to the slight dimensional changes.

Titanium carbides with nickel binders (Kennametal 150A) were irradiated under the same conditions as the Carboloy materials. Specimen lengths increased and widths decreased by small percentages (0.1–0.23%). Densities decreased 0.3–0.6%.

Tantalum and tungsten densities decreased 0.10 and 0.15%. It decreased 0.20–0.25% for tantalum-tungsten alloy.

Thus, it is seen that large density changes are confined to sintered carbide materials.

Magnetic Susceptibility

Stainless steels tested by ORNL's Metallurgy Division increased in magnetic susceptibility after 10^{19} nvt slow. The types (and Guoy-method magnetic-susceptibility percentage increases) were: two 304 specimens (533 and 528), 309 (179), 316 (684), and 347 (563). Type 309 (25% Cr, 12% Ni) was affected less than the 18-8 types (its austenite is more stable).

Austenitic, ferritic, and precipitation-hardening stainless steels were irradiated in flowing 540° F water for 3×10^{19} nvt slow. Measurements were made with an Aminco-Brenner Magne-Gage. The types (and average percentage susceptibility increases) were: 329 annealed (0), 347 Cb-Ta annealed (100), 347 Cb-Ta shot-peened (350), 431 hardened (14), 431 annealed (20), 442 annealed (5), Armco 17-4 PH hardened (4), 17-7 PH hardened (11), 17-7 PH Malcomized (30), USS "W" hardened (10). Austenitic stainless steels, types 347 columbium-tantalum annealed, 347 columbium-tantalum shot-peened, and 329 annealed, were only slightly magnetic before irradiation and the relative increases noted were large. Ferritic and precipitation-

TABLE 3—Radiation's Effect on Notched and Unnotched Nickel Alloys

Material*	nvt (10^{19} n/cm²) Slow	Fast	Temp. (°F)	U.T.S. (10^3 lb/in.²)	Elongation (%)
Monel					
U	0	0	70–140†	85.0	33
U	5	4	70–140†	96.0	10
U	0	0	~70‡	86.0	31
U	0	0	~70‡	87.5	34
U	4	—	540§	91.5	29
N	0	0	70–140†	129.0	—
N	5	4	70–140†	¶	—
N	0	0	~70‡	127.5	2
N	0	0	~70‡	131.0	2
N	4	—	540§	133.5	1
K-Monel					
U	0	0	70–140†	123.0	11
U	5	4	70–140†	134.0	3
U	0	0	~70‡	127.0	12
U	0	0	~70‡	124.0	9
U	4	—	540§	133.5	19
N	0	0	70–140†	211.0	—
N	5	4	70–140†	226.0	—
N	0	0	~70‡	212.5	1
N	0	0	~70‡	209.0	1
N	4	—	540§	195.0	2
Inconel					
U	0	0	70–140†	106.0	31
U	5	4	70–140†	116.0	29
U	0	0	~70‡	108.5	33
U	0	0	~70‡	107.5	28
U	4	—	540§	113.0	29
N	0	0	70–140†	151.0	—
N	5	4	70–140†	172.0	—
N	0	0	~70‡	148.0	1
N	0	0	~70‡	153.0**	2
N	4	—	540§	160.0	2
Inconel-X					
U	0	0	70–140†	126.0	37
U	5	4	70–140†	133.0	23
U	0	0	~70‡	129.5	38
U	0	0	~70‡	128.0	35
U	4	—	540§	139.0	35
N	0	0	70–140†	174.0	—
N	5	4	70–140†	203.0	—
N	0	0	~70‡	173.0	2
N	0	0	~70‡	175.0	2
N	4	—	540§	198.0	1
Hastelloy-C (wrought)					
U	0	0	70–140†	138.0	20
U	5	4	70–140†	142.0	12
U	0	0	~70‡	142.0	21
U	0	0	~70‡	138.5	19
U	4	—	540§	137.0	36
N	0	0	70–140†	198.0	—
N	5	4	70–140†	220.0	—
N	0	0	~70‡	204.0	1
N	0	0	~70‡	192.0	—
N	4	—	540§	191.0	2
Hastelloy-C (cast)					
U	0	0	—	76.0	—
U	4	5	—	104.0	—
U	0	0	—	85.0	—
U	4	5	—	111.0	—

* U = unnotched specimens; N = notched specimens. † In dry sealed containers. ‡ Stored in air at room temperature so as to accentuate the effects of irradiation and in-pile corrosion. § In flowing water. ¶ Erratic. ** Specimen prestressed before testing in an effort to approximate the effects of irradiation.

TABLE 4—Radiation's Effect on Impact Properties of Boiler Steels*

Material	nvt (10^{19} n/cm²) Slow	Fast	Temp. (°F)	Transition temp. change (°F)	Max. energy change (%)
SA-70					
	7.5	—	125	+125	−41
SA-212					
	9	8	125	+115	−23
	9	8	125	+170	−29
	0.8	0.2	580	+45	−5
	0.8	0.2	425	+35	−7
Aluminum-killed 0.34-carbon steel					
	0.8	0.2	425	+20	−4
	0.8	0.2	390	+20	−2
	0.8	0.2	350	+20	−4

* Small specimens were used, thus values and ranges of absorption are relative.

* C. T. Herty, D. L. McBride, *Mining Met. Invest. U. S. Bur. Mines, Carnegie Inst. Technol. and Mining Met. Advisory Boards*, Bull. 67 (1934).

hardening alloys displayed higher initial values and relatively smaller increases. A type-446 hardened specimen showed an 18% decrease. Moreover, a 5% decrease was noted for type-446 specimens irradiated in 540° F flowing water for 5×10^{20} nvt slow and 4×10^{19} nvt fast. Control specimens showed no change.

Irradiation probably causes some phase transformation from austenitic to ferritic iron, as indicated by magnetic susceptibility changes. However, the amount transformed is not sufficiently large to indicate any appreciable increase in the corrosion susceptibility of common stainless-steel types.

Electrical Resistivity

ORNL's Metallurgy Division reports that quench-annealed stainless steels (types 304, 309, 316 and 347) and nickel-base alloys (Nickel-A and Hastelloy-C) underwent small changes after being irradiated in 400-500° F flowing water for 10^{19} nvt slow.

Austenitic stainless steels, types 304, 309, and 347 showed 5% increases in electrical resistivity after 5×10^{20} nvt slow and 4×10^{19} nvt fast in 540° F flowing water. The ambient temperature might have annealed larger changes.

Tantalum's electrical resistivity remained fairly constant after 10^{19} nvt slow and 5×10^{19} nvt fast. Tungsten's resistivity increased 40%.

CONCLUSIONS

The data indicate that engineering properties of reactor structural metals are not affected catastrophically by irradiations up to about 10^{20} nvt slow.

Further work is needed to separate the variables of fast flux, exposure time and temperature. The apparent approach to damage saturation must be verified. Because accumulated irradiation as high as 10^{24} nvt might be encountered in central station operations, metals must be studied in these high flux ranges.

* * *

This article is based on a paper presented at the American Institute of Chemical Engineers' International Congress on Nuclear Engineering, Ann Arbor, Michigan, June 20, 1954. Post-irradiation experimental work was performed by the metallurgy divisions at Argonne and Oak Ridge National Laboratories and by the reactor engineering division at Argonne National Laboratory. Appreciation is due particularly to Karl F. Smith, S. H. Paine, Jr., W. F. Murphy, and J. E. Kemme for their assistance and many helpful discussions and suggestions during the course of the investigation.

New Designs For Power:

Fluidized- and Liquid-Fuel Reactors with Uranium Oxides

Gaseous or heavy-water suspensions of natural or slightly enriched uranium can provide good heat transfer, integral processing, a high conversion ratio and possibly self-control of reactivity when they are used as a movable fuel for a power reactor. Several flow schemes have been evolved from rheological reactor-model studies

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HIGH HEAT TRANSFER RATES and continuous purification make liquid-fuel reactors very attractive for power. Two types of such reactors that use natural or only slightly enriched uranium are considered in this article. One type uses heavy water both as moderator and suspension liquid; the second type uses a fluidized bed of dry particles that makes higher outlet temperatures feasible. Both types make high conversion ratios possible. Several constructional details and assemblies described in this article are also applicable to highly enriched reactors.

D_2O Suspension Reactors

A large thermal reactor with only uranium, deuterium and oxygen in the core will probably be a breeder. Uranium oxide particles suspended in heavy water, to fuel a homogeneous reactor, fit this ideal bill of materials. Heterogeneous suspension reactors are also feasible. The first type cannot be made critical with natural uranium at high temperatures, making slightly enriched uranium necessary. If the second type is heterogeneous both geometrically and thermally, it is probably possible with natural uranium, even at high temperatures. The tubes, containing the concentrated suspension and providing thermal insulation

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between suspension and moderator, should absorb few neutrons.

Feasibility problems. In a suspension reactor the following conditions should be fulfilled:

1. Suspension should be stable in a colloid-chemical sense. This means no flocculation can occur and that particles contacting one another can easily separate again. This stability has to be maintained at the high temperatures (250–300° C) desirable in a power reactor.

2. Unavoidable settling should not disturb the homogeneous particle distribution in the suspension and in that way alter the local reactivity. The large difference between the specific density of uranium oxides (UO_2–10.9 and U_3O_8–7.3) and that of heavy water (1.1) implies a high rate of settling. Therefore special attention should be paid to the settling problem.

3. Suspension should remain sufficiently stable and homogeneous under reactor conditions.

4. Viscosity of the suspension should be small, so that it can readily be pumped through an external heat exchanger.

5. Extremely reliable pumps, without moving parts, should be used for the highly radioactive suspension.

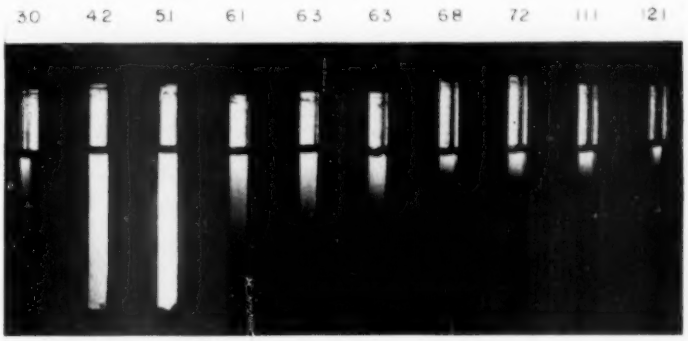
6. The diameter of the particles should be smaller than the mean free path of the fission products, so that most fission nuclei will leave the particle and an automatic separation of fuel and poisoning fission products occurs. In uranium oxides the mean free path is about 10–15μ. In dilute suspensions, as in the present case, the fission nuclei will be stopped in the water phase. Plutonium will remain within these relatively large particles.

Suspensions. Of the different uranium oxides UO_2, U_3O_8, UO_3 and intermediate oxidation states, UO_2 with its highest uranium content is of most interest. It is very likely that the surface of all oxides consist of hexavalent uranium oxide in hydrated form. Therefore it is understandable that the stability measurements of UO_2 and U_3O_8 give the same results. Studies such as shown in Fig. 1 prove that flocculation can be avoided.

As the viscosity of heavy water diminishes considerably with rising temperature, the settling velocity (not the stability) increases with temperature to relatively high values.

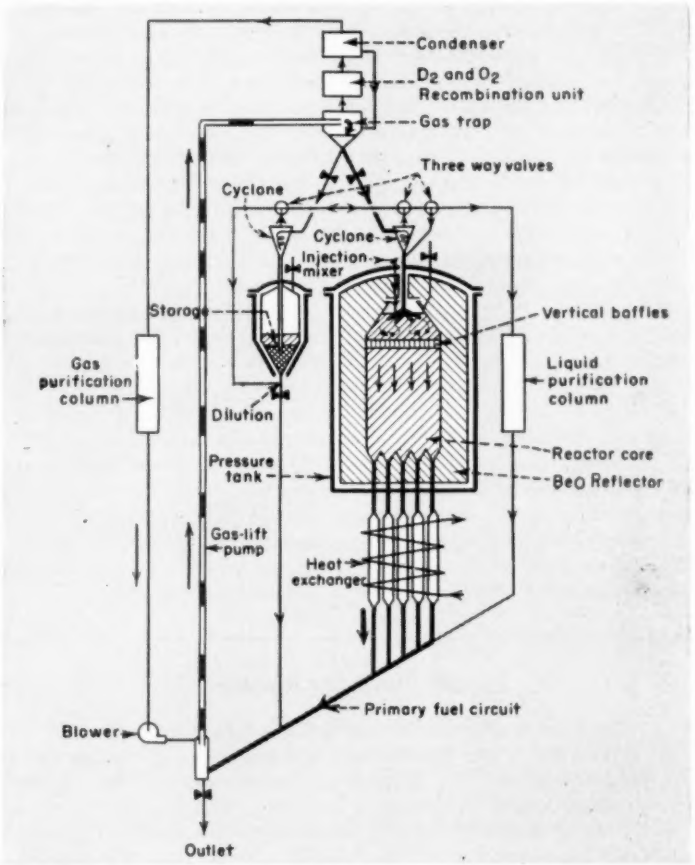
The effect of radiation and the fission

1. Uranium-oxide suspensions in heavy water are stable, don't flocculate, so that . . .



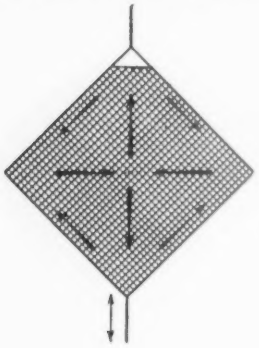
SETTLING VELOCITY STUDIES of fine UO_2 powders show no flocculation in waters of 6.3 to > 10 pH at room temperature, 1 atmosphere pressure. Settling time before photographing is 1 hour. At 250° C and 35 atmospheres, stability still exists

2. Homogeneous liquid-suspension reactor is feasible. Heavy water imposes 300° C limit



LIQUID SUSPENSION REACTOR uses injection mixer above core to homogenize fuel. Vertical partitions reduce cross-flow. Downward water flow at settling velocity maintains suspension uniformity. Construction has been tested, simulating 10 μ UO_2 particles in 300° C water. Gas-lift pump circulates fuel. Cyclones at reactor and storage inlets control particle concentrations. Ideal heat exchange inside core results in automatic internal reactivity adjustment. BeO reflector reduces neutron capture by tank walls

3. Dry suspension can be fluidized by vibration, and . . .



IDEAL HOMOGENIZATION of dry powder occurs in vibrating double cone. Section through cone shows circulation caused by vertical oscillation. Basis is the fact that powder will move along a flat surface vibrated in a direction at an angle of 30–60 degrees with that surface

process has been investigated in the JEEP reactor (*1*). At a flux of 8×10^{11} n/cm²/sec, the stability remains. Effects of higher fluxes are still unknown. Flocculation by polyvalent ions originated from fission products that are transferred to the water phase need not be feared as their concentration will always be extremely low.

Pumps. A rotating pump seems too vulnerable for the highly radioactive suspensions, and electromagnetic pumps are not suitable due to the low electrical conductivity of the suspension; therefore gas-lift pumps should be used. The difference in over-all specific weight of the suspension with a large gas content in the gas-lift pump and of the suspension without gas in the reactor and heat exchanger supplies the lifting force (see Fig. 2). The efficiency of a gas-lift pump (about 40%) is smaller than that of a rotating pump (about 75%). A second disadvantage is the relatively large volume of the pump. On the other hand, the construction is extremely simple and reliable, and the gas stream bubbling through the suspension removes volatile fission products such as Xe, Kr, I (I^{135}), Br and TeO_2. This means that a large amount of the β (and γ) activity is removed, more or less automatically (*2*).

Reactor design. The principal design problem is maintaining suspension uniformity without any moving parts in the core. As Fig. 2 shows, this is solved by placing an injection mixer above the core to homogenize the inlet fuel. The uniform fuel slurry then flows downward through the core at a velocity equal to the settling velocity of the suspended uranium oxide particles. With no relative motion of particles and water inside the core itself, no trouble arises from uneven particle distribution.

Discharging the completely settled suspension from the storage tank is done by dilution. The low fluidity of the settled suspension is increased several times by adding 10% water to the slurry.

Absence of internal parts means the conversion ratio will be high. This type of reactor has automatic internal reactivity adjustment (*3*) because of the ideal heat contact between the fuel and heavy-water coolant.

Two items, the uranium concentration desirable to make the reactor as insensitive as possible to concentration fluctuations and the effect of dilution with Th^{232} as Pu^{239} is formed, need additional work.

Advantages. The homogeneous wet suspension reactor is very simple in construction and has internal temperature regulation. Heat extraction can be as high as 25 Mw/ton U when the entire water content of the reactor is used for heat removal.

Heterogeneous D_2O Reactors

Heterogeneous suspension reactors use a completely settled suspension flowing through tubes inside a heavy-water tank. These reactors can be made critical with natural uranium. Their construction and operation, however, is much more complicated than that of the homogeneous reactor. Velocity of the suspension must be adjusted separately for each ring of tubes, to avoid outlet temperature differentials.

Fluidized-Fuel Reactors

Both of the liquid suspension types are limited to 300° C outlet, because of the critical temperature of heavy water (371° C) and high pressures (35–80 atmospheres) in the reactor tank. Fluidized dry suspensions can raise the temperature limit while retaining the advantages of fuel mobility.

For several decades a method for fluidizing solid particles in a gas stream has been known. Since the last World War these fluidized systems have been used industrially for catalytic processes and heterogeneous chemical reactions at temperatures up to 600–700° C. Therefore the possibility of using fluidized fuel systems is attractive.

Fluidization is possible by blowing a gas stream through a bed of solid particles. At low gas velocities the pressure necessary is proportional to the gas velocity. At a rather well defined gas velocity the particles are loosened a bit resulting in looser packing of the particles. The powder is fluidized, and the pressure does not increase with an increase in gas velocity. This state, still a dense packing, is called the *liquid-expanded state*. If in such a liquid-expanded bed the gas velocity is further increased, large gas bubbles pass through and the particles are mixed thoroughly. This state is called *the boiling state*.

Liquid Fuels for Reactors

Four different types of liquid fuels can be distinguished:

A. Solutions of uranyl salts in water or heavy water. Several reactors of this type have been built (4). It is easy to insure by means of solution a homogeneous distribution of uranium.

B. Solutions or suspensions of uranium in a heavy liquid. By using a liquid with a density comparable to that of the uranium containing particle, a homogeneous slurry is possible. The LMFR (5) uses U^{233} dissolved in bismuth or U-Sn_3 dispersed in lead-bismuth-tin.

C. Suspensions of uranium containing particles in water or heavy water.

D. Fluidized dry suspensions of uranium containing particles.

The last two types are considered in this article.

Boiling beds are used in industry on a large scale as they ensure thermal homogenization. However, the boiling state is intolerable inside a reactor, as reactivity would change too much and too fast.

Two other means of fluidization may be used. One is the *vibrating bed* (Fig. 3) in which complete mixing occurs. Gas is not important in this system. The dimensions of this type of vibrating reactor vessel are rather limited, as the energy demand increases too much with size.

The other type of particle movement is the "sandglass" motion caused by gravity and called the *moving bed*. Particle mixing occurs to a slight degree, if at all, in this movement.

Enrichment vs reactor design. Either homogeneous or heterogeneous reactors with fluidized solid fuels can be built. However in the homogeneous reactors a mixture of UO_2 and BeO must be used, that means the fuel must be moderately enriched. Since a vibrating reactor vessel should be small, highly enriched fuel would be needed. As we are interested in natural or slightly enriched uranium reactors, only the heavy-water-moderated fluidized heterogeneous type is discussed.

Reactor design. The heterogeneous fluidized UO_2 reactor fuel circuit (Fig. 4) employs all three means of moving solids: moving bed through the reactor tubes, homogenization at the outlet by a vibration unit, and gas fluidization from then on in the heat exchanger.

Low cross section material like BeO is desirable for the reactor tubes. These are believed technically possible. As thermal insulation between tubes and moderator, porous BeO bricks containing stationary heavy water could be used. This insulation is such that through a 1-cm layer not more than a few per cent of the fission energy will be removed.

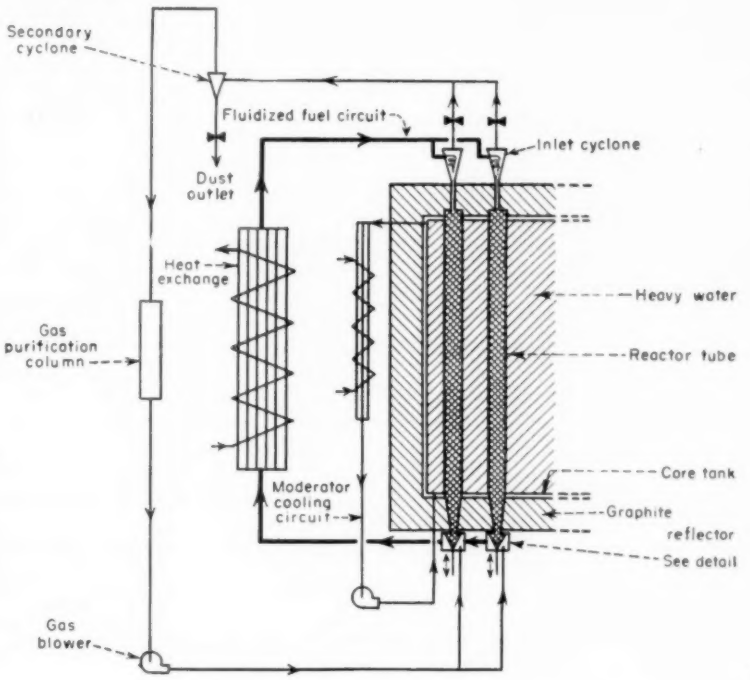
Pneumatic material transport through the external heat exchanger will not cause important erosion. The hardness of uranium oxides is only about Moh 4, and therefore erosion of the uranium oxide itself is probable.

Advantages. The heterogeneous fluidized reactor offers several important advantages compared to its counterpart, the heterogeneous settled wet suspension type. The temperature is not limited to 300° C; 600–700° C is quite feasible. Even at such high temperatures no pressure is needed in the system. The adjustment of velocity inside the tubes is much easier with this sandglass vibrating-bed system. Moreover in the heat exchanger and all pipe lines, cyclones, etc. outside the reactor, the expensive heavy water is not needed. Finally, it is important that this reactor can be operated with natural uranium.

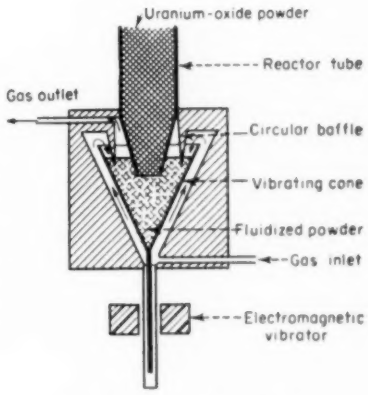
* * *

The authors wish to acknowledge the assistance of M. E. A. Hermans who made the stability measurements. Patents are pending on several of the details and assemblies described. This article is based on a paper presented at the American Institute of Chemical Engineers International Congress on Nuclear Engineering, Ann Arbor, Michigan, June 23, 1954.

4. Heterogeneous fluidized-fuel reactor can operate at 600° C or higher



HETEROGENEOUS REACTOR is fueled by dry suspension flowing through BeO tubes as moving bed. Vibrating discharge unit fluidizes particles leaving reactor. Preheated gas stream transports fuel through heat exchanger to reactor inlet cyclones that separate gas from solids. Secondary cyclone removes UO_2 dust formed by erosion in fluidized section. Graphite reflector reduces neutron leakage. Separate cooling circuit keeps heavy-water moderator at 50° C



Detail of vibrating discharge unit

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ALVIN M. WEINBERG, research director of Oak Ridge National Laboratory, Oak Ridge, Tennessee

Weinberg says we need:

"A Scholarly Tradition in Nuclear Development"

The uncurbed pace of nuclear development has created a wealth of practical experience, but only at the expense of curtailed growth of theoretic, historic and pedagogic doctrines underlying the technology. This article tells why these fundamentals, the core of a scholarly tradition, must be developed

MY PRIMARY AIM in this article is to urge the establishment and strengthening of a scholarly tradition in nuclear technology.

I ought first to explain what I mean by the scholarly tradition in a heavy technology. All important heavy technologies—for example, aeronautics, heat engineering, or communications engineering—have developed along two complementary paths. On the one hand, there is a body of practical experiences and practical successes—the DC-7's or the Ljungström turbines or the TV networks—with which most of the technicians are concerned and upon which most of the money is spent. On the other hand, there is the body of theoretic, historic, and pedagogic doctrine that underlies the technology and that is the concern of the technology's "longhairs" and professors. It is the pursuit and expansion of this theoretic, historic, and pedagogic doctrine that I call the scholarly tradition.

How do we recognize a well-developed scholarly tradition in a technology?

First, we notice that scientists in the field are not self-conscious or apologetic about pursuing their careers. For why be self-conscious when there exists a community of authorities with a common language who understand and appreciate one's contribution?

Again, the tradition is well developed if there is a scholarly journal read by all who would understand the field; if there are treatises and recognized authorities; if there is pedagogic activity at the highest level; if it is not necessary to start every technical discussion with preliminary baby talk; if the most exacting standards are used in judging a piece of research, even though less than the ultimate in care is sufficient to make the results practically useful. Above all, the tradition is well developed if there are *scholars* in the field: people who take pleasure in understanding the technology's fine points and history.

It is evident that nuclear development has, for various reasons, been handicapped in establishing a scholarly tradition.

Secrecy has surrounded the development. One can hardly have a completely healthy community of investigators if the basic facts are available to only a few. This situation was embarrassing at the Oslo heavy-water reactor conference; every so often the American, British, or Canadian delegates would have to drop out of a discussion that veered toward the classified.

The effect of secrecy is made more acute because a scholarly tradition is ordinarily nurtured and resides in the universities and institutes of technology. But the new knowledge upon which the nuclear tradition builds is developed—because of both secrecy and expense—in the National Laboratories or in the industrial nuclear development laboratories. Thus the scholars of the technology, the university professors, must often be content with a somewhat dilute contact with the technology whose tradition they are expected to establish.

I believe secrecy is only one, and possibly not the most important, reason for the comparative lack of a recognizable scholarly tradition in nuclear development.

There is, of course, the fact that barely 12 years have passed since the first chain reaction was achieved. Almost by definition a tradition takes time for its establishment. These 12 years have been spent in frenetic activity: the military implications of the work are so important that few have time to sift over the fine details, to tidy up the thinking. Again, because everyone is so extremely busy, there has been too little opportunity either to record the technology's state or to assimilate its history. All of this is much aggravated, at least in our country, because we do our work on so lavish a scale, and because we are necessarily in a hurry to build operable gadgetry; it is impractical to take the time necessary to see that every detail is completely understood, if an approximate theory or expensive integral method will give a usable result.

An excellent example of how our understandable necessity for *building* reactors has influenced our approach to the fundamentals is afforded by our experience relative to the Canadians during the war.

Since we were primarily responsible for, and had the money to build, a large-scale chain reactor as soon as possible, we were not able to devote much time to the higher-order diffusion theory. Instead we used a simple diffusion approximation in all our design calculations. Placzek and his group in Canada, not being perpetually importuned by engineers who wished to build something on an implacable schedule, had more time; the beautiful and painstaking work they did on the high-order corrections to lattice theory still stand among the most significant contributions to reactor theory.

As has every other technology, nuclear technology has in some sense become a rejected child of its parental basic sciences. We physicists, I suppose, are perhaps the most unnatural parents in this regard; some of us have long since begun to call binding-energy nuclear physics "engineering." As for reactor physics, I have heard at least one brilliant theoretical physicist interested in group theory dismiss reactor physicists as "Bessel function" physicists, perhaps unaware that the greatest group theorist, Eugene Wigner, is also the greatest reactor physicist.

In some quarters concern with nuclear development has become a slightly unrespectable occupation.

It seems to me that the development of a sound and vigorous scholarly tradition in nuclear energy will do much to dispel this unhealthiness. What is important or interesting in science is, if we are honest, in surprisingly large degree determined by what the community of investigators thinks is important and interesting. There are innumerable examples of fields of science that have withered, not because they have become less important but because they have become less fashionable. The development of a strong tradition, especially in the universities, in the specialties underlying nuclear energy—for example, binding-energy nuclear physics and reactor physics, transport and reactor theory, radiation chemistry and metallurgy, mammalian radiation biology—will insure the kind of continued interest in our technology that we expect and need from our coming generations of scientists.

One way in which the scholarly tradition is growing in the universities is by people from the atomic energy projects moving into the universities and establishing curricula in nuclear energy.

I might mention Professor C. K. Beck and the group at North Carolina State College who operate the first university research reactor; or Professor Manson Benedict and his nuclear engineering curriculum at Massachusetts Institute of Technology; or the several universities, among them Penn State, University of Michigan, Vanderbilt University, which are planning to build nuclear reactors. With the expected relaxation in secrecy we can hope that the beginning of the scholarly tradition represented by these university activities will be much enhanced.

It is particularly appropriate to discuss the scholarly tradition on two accounts: First, because the existence of new professional-society activities in the field of nuclear technology are a manifestation of such a tradition; and second, because recent meetings in the United States have been graced by the presence of so many British and other European atomic energy representatives.

We in the U. S. have always looked toward our European friends for much of the fundamental thinking in our technologies. We are not unmindful of the strongly dominant position occupied by scientists of European origin at the beginning of the American project, of the intellectual inspiration given to us by Fermi, Szilard, and Wigner.

Although American work in nuclear energy now proceeds on a colossal scale, we still believe that there is a need and a place for pursuit of the technology on a smaller, more leisurely, and more scholarly basis than it is pursued here.

We are much impressed in our country with the pre-eminence of the British group around B. Davidson in the field of transport theory, with the beautifully elegant integral neutron experiments by Von Dardel of the Swedish group, and with the daring technological advances, in the best tradition of French engineering, represented by the high-pressure nitrogen-cooled reactor at Saclay.

At the banquet given for the visiting delegates at the Oslo meeting by the Christian Michelsen Institute, Dr. Randers, head of the Norwegian project, spoke, perhaps wistfully, of the Materials Testing Reactor, which exceeds the flux of most European reactors by two orders of magnitude. Dr. Randers asked how European countries, incapable of putting as much money into the development, could expect to compete with us. I hope these remarks serve to answer Dr. Randers: that while we have more money per technician, we have no more brains, and we certainly have less time than the Europeans.

Of the commodities necessary for establishing and nurturing the scholarly tradition, I would place money a poor third to time and brains.

We Americans shall therefore continue to look to the European nuclear technology for a good share of the profound intellectual endeavor upon which the scholarly tradition, and therefore the long-term success of the technology, must ultimately depend.

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This article is based on a speech presented at the American Institute of Chemical Engineers' International Congress on Nuclear Engineering, Ann Arbor, Michigan, June 22, 1954.

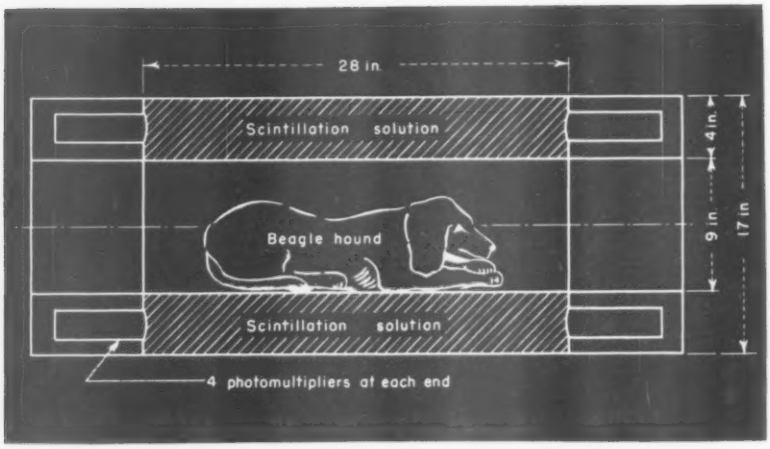

FIG. 1. Annular dog counter (K-9) utilizing liquid phosphor and eight photomultipliers

K-9:

A Large 4π Gamma-Ray Detector

The K-9 annular scintillation counter accommodates a 9-kg dog for whole-body measurements. Utilizing 8 photomultipliers, the counter is relatively insensitive to source position; lower detection limit is 0.002 μg radium in a dog

By M. A. VAN DILLA,* R. L. SCHUCH,† and E. C. ANDERSON†

IF RADIOACTIVE MATERIAL retained by an experimental animal emits penetrating γ-rays, external measurements can be made with G-M counters (*1*), scintillation counters (*2–4*), or ion chambers (*5, 6*). Development of large liquid scintillators (*7–9*) has made it possible to construct a cylindrical scintillator large enough to accommodate an adult beagle dog (Figs. 1 and 2).

Theory

The problem for which this counter was designed is the determination of the quantity of γ-ray emitter contained in dogs (beagles) of relatively standard weight (9 ± 1.5 kg) independent of variations in the distribution of the radioactive material in the animal and the degree of self-absorption in the tissues. The radioactive materials used in these experiments are Ra^{226}, Ra^{228}, and Th^{228}. These nuclides are all bone seekers and are the parents of γ-emitting daughters.

4π counter. The problem of unknown geometry can be solved with a 4π γ-ray counter large enough to surround the source completely. If all parts of such a counter have uniform sensitivity and if the liquid thickness is a number of mean free paths of the emitted photons, then output counting rate is independent of the position of a source of negligible self-absorption inside the counter. In such a counter, all the photons emitted by the source are absorbed in the liquid scintillator irrespective of source position. If the resultant light from all parts of the liquid diffuses to the viewing photomultipliers with equal efficiency, output counting rate is independent of source position.

Self-absorption. Gamma-ray attenuation in the source itself may not be negligible. In the case of beagles that have been injected with radioactive materials, the emitted γ-rays have quantum energies of the order of 1 Mev and a mean free path of about 5 in. of water (or soft tissue). Hence self-absorption cannot be ignored.

To get a qualitative idea of self-absorption effects, consider the case of a small γ-ray source ($h\nu = 1$ Mev) inside a slab of water d in. thick. Let the source be a distance x from one face of the slab and $d - x$ from the other; consider only transmission in the x direction and ignore scatterings other than the first. If $d < L$, where L is the mean free path of 1-Mev γ-rays in water (about 5 in.), then the fraction

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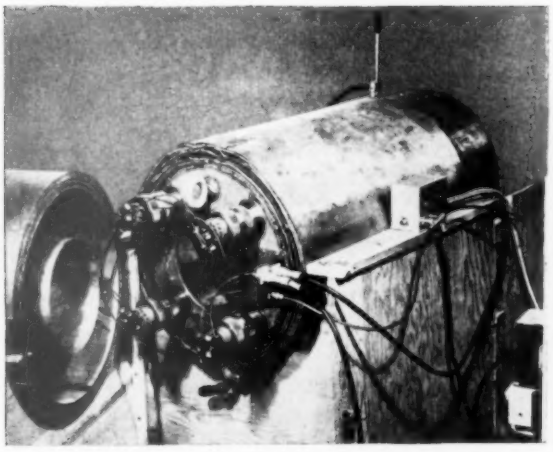

Fig. 2. Lead shield, 1 in. thick, reduced background by $\frac{1}{3}$

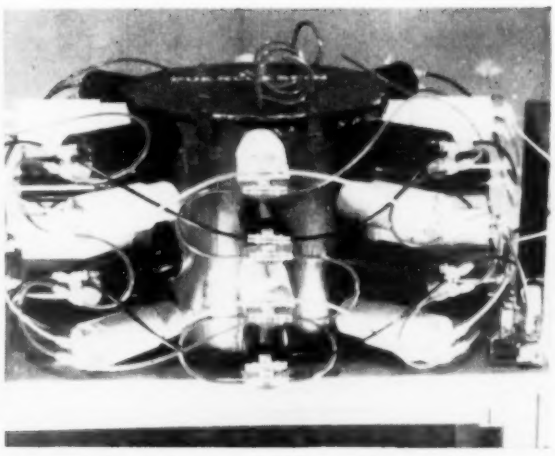

FIG. 3. Two-cubic-foot cylindrical detector (32 tubes)

I/I_0 of γ-rays emerging from one face of the slab is

$$\frac{I}{I_0} = \left[\exp\left(-\frac{x}{L}\right) + \exp\left(-\frac{d-x}{L}\right)\right] \Big/ 2 = 1 - d/2L \qquad (1)$$

and hence very nearly independent of x. Even if d is approximately equal to L, emergent intensity varies relatively little with x. Thus, for $d = 6$ in. and $L = 5$ in., calculation of I/I_0 as a function of x shows that I/I_0 varies between a maximum value of 0.65 at the surface ($x = 0$ or 6 in.) and a minimum value of 0.55 at the center ($x = 3$ in.) or $\pm 8\%$.

This is, of course, a much over-simplified example, since it ignores multiple scattering and the degradation in energy of the scattered photons. It serves, however, to indicate that response of a 4π counter should be relatively insensitive to source position even when the source is moved around inside an absorbing medium.

Design

The number of photomultipliers to be used is one of the principal problems involved in the design of large scintillation detectors. Because of the expense of the photomultipliers and the difficulties of installation and maintenance, it is desirable to reduce the number to the minimum consistent with adequate pulse height and energy resolution.

In earlier work with large liquid scintillators, where both uniform and high-energy resolution was essential, 2.5% of the total wall area was occupied by photocathodes (32 tubes for the 2-ft^3 cylindrical pilot model, Fig. 3) (7).

Since the pulse-height spectrum from the complex gamma radiations of the Ra, RdTh, MsTh, and their daughter products was expected to be diffuse, especially after degradation in the dog, no attempt was made to obtain good resolution over the detector volume. Rather, resolution was deliberately sacrificed for photomultiplier economy.

Preliminary study. To establish the extent to which the number of tubes could be reduced, a preliminary study was made using a 2-ft^3 cylindrical detector (16-in. diameter and 16-in. height) originally designed (7) with 32 type 5819 photomultipliers connected in parallel (Fig. 3). Integral counting rate was measured for background and for a 0.1-μc Ra ampule placed in the center of the detector solution. The discriminator was set at 0.5, 1.0 and 2.0 Mev, and the number of photomultipliers contributing to the signal was varied. Results are shown in Table 1.

Since this detector has sufficient energy resolution to show a peak in the differential pulse-height spectrum of a single γ-ray emitter, there are comparatively few low-energy pulses in the spectrum.

With fewer tubes, the light-collection efficiency is smaller and varies more over the volume of the detector. This has the effect of broadening and shifting the differential spectrum to lower energies. If the integral gate is set low enough, the only pulses lost are those few that are initially just above the gate setting; thus integral counting rate is essentially unchanged by reducing the number of tubes. If the number of tubes is reduced too far, tube noise begins to appear and background rises rapidly. Energy resolution, of course, becomes progressively poorer as tubes are removed. Note that the counting efficiency for a discrimination level of 0.5 Mev is about 0.60 count per radium disintegration.

Design of K-9

On the basis of the preceding results, it was concluded that eight photomultipliers (four at each end of the annular sensitive volume) would be adequate for K-9 (Fig. 1). Because of the inferior light collection in the K-9 annular geometry, as compared with cylindrical geometry, it was thought undesirable to try fewer tubes.

The liquid scintillator is contained between two coaxial cylinders, each 28 in. long, one having a 9-in. diameter and the other a 17-in. diameter; thus the sensitive volume is a cylindrical liquid shell 28 in. long, 9 in. i.d., 4-in. wall thickness, and with open ends. The photomultipliers were placed at both ends of the shell to minimize the mass of shielding required.

Counter efficiency. In K-9, the eight photocathodes constituted about 0.5% of the total wall area. If the

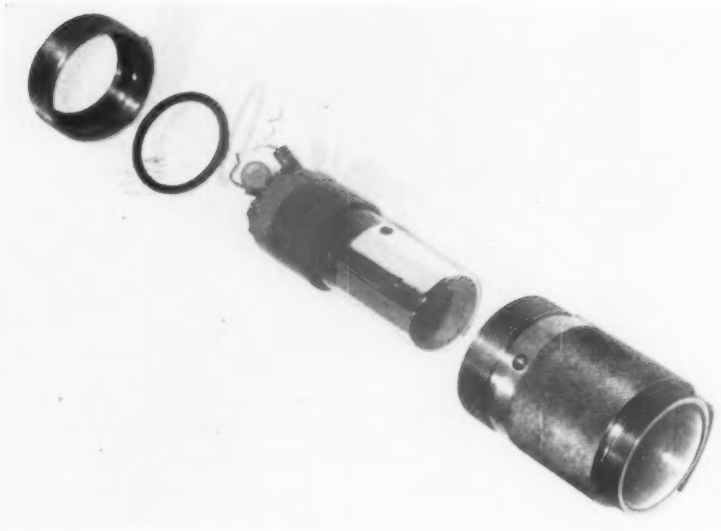

FIG. 4. Method of mounting photomultipliers

TABLE 1—Effect of Number of Photomultipliers on 2-ft³ Cylindrical Detector

No. of tubes	0.1 μc Ra net cps; integral rate above energy E: E = 0.5 Mev	1.0 Mev	2 Mev
	Signal		
32	2,170	1,490	470
16	2,100	1,350	243
8	2,220	1,250	167
4	2,220	770	123
1	(unstable)*	260	12
	Background		
32	2,500	1,320	520
16	2,200	1,140	427
8	2,500	960	343
4	2,500	835	294
1	4,900*	430	150

* Tube noise now contributing.

detector were spherical with the cathodes uniformly distributed (which is true to a good approximation for the 2-ft³ cylindrical counter), then the fraction, S, of the emitted light eventually reaching the photocathodes would be approximately

$$S \approx F[1 + rt + (rt)^2 + \ldots] = F\,1/(1 - rt) \qquad (2)$$

where F is the fraction of wall area covered by the photocathodes, r is the reflectance of the wall coating multiplied by $(1 - F)$, and t is transmission of the solution for the average light path between reflections. In practical detectors, F is small (of the order of 1%). However, as both reflectance and transmission approach unity, S approaches unity and all the light is collected. Although this theoretical limit cannot be reached in practice, good reflectance and transmission make S considerably larger than F. For example, if $rt = 0.8$, then $S/F = 5$; if $rt = 0.95$, $S/F = 20$. Both r and t must be close to unity for S/F to be much greater than unity; that is, it does no good to improve one if the other is poor.

In the case of annular-geometry counters (as K-9), Eq. 2 does not apply even approximately. A considerable number of reflections is required for light created in the middle of the scintillator to reach the photocathodes at the ends. The number of reflections per meter of light path is larger than for the cylindrical detector. In fact, the number of reflections per meter of light path is inversely proportional to annular thickness. Therefore, high wall reflectivity is more important in annular counters than in cylindrical counters.

The problem of transmission through the solution has been solved by proper solvent choice and purification and by the use of secondary solutes to shift the emission spectrum to longer wavelengths. For example, the mean free path at 4,150 Å in purified toluene is 300 meters and in purified triethyl benzene is ~3 meters.

The problem of a suitable reflecting surface still awaits satisfactory solution. The preceding rough analysis emphasizes the extreme importance of this problem in improving light collection and conserving photomultipliers. In the present studies, white Tygon enamel* was used, where triethylbenzene is the solvent. This enamel is not sufficiently toluene resistant, and Pacific white baking enamel† is used with toluene. Unfortunately, the pigment in both these enamels appears to be TiO_2, which, as pointed out by P. R. Bell, has very poor reflectance below 4,000 Å. Unless secondary solutes are added to shift the emission spectrum of terphenyl (3,300–3,800 Å) or of diphenyl oxazole (3,500–4,000 Å) to longer wavelengths (*10, 11*), the reflectivity is quite poor (50% or less at 3,800 Å). Addition of alpha-naphthyl phenyl oxazole, which moves the emission spectrum to 3,900–4,600 Å (peak at 4,150 Å), greatly improves reflectance. The search for better reflectors is being continued.

Construction. The detector tank is stainless steel, the ¼-in.-thick outer wall being welded to the ⅜-in.-thick end plates. The inner wall, 0.015 in. thick, was welded in place, and the interior was painted with white Tygon paint to improve the light collection by the photomultipliers.

To provide a simple, easy method of changing tubes as well as minimizing the danger of leakage, the tube-mounting system shown in Fig. 4 was used. The knurled metal sleeve has a 3-mm-thick curved-glass window (optical lens quality to insure sufficient strength) cemented into the end with Armstrong A-1 adhesive.‡ The sleeve screws into the detector tank, and a tight seal is provided by a Vellumoid gasket impregnated with clear Tygon paint. The photomultiplier is held in position by the O-ring fitting around the tube base and squeezed inward by a bevel cut inside the rear lock-ring. Since pressure on the O-ring is normal to the photomultiplier axis, the tube can be locked into any desired position with respect to motion along the axis. It is therefore possible to adjust the tube face to any position with respect to the window regardless of tube length.

* U. S. Stoneware Co., Akron, Ohio.

† Pacific Paint and Varnish Co., San Francisco, Calif.

‡ Armstrong Products Co., Argonne Road, Warsaw, Indiana.

Each photomultiplier must be optically coupled to its curved-glass window to obtain maximum light collection. Since the end window of the RCA 5819 photomultiplier has a rather irregular shape, a thin Lucite disk was cemented to it with an optically clear cement.* This Lucite disk was molded to the same curvature as the 3-mm-thick curved-glass window. Thus, only a small amount of silicone stopcock grease was needed to couple the photomultiplier optically to the curved-glass window. Note that the photomultiplier shown in Fig. 4 has not yet been treated in this way.

The scintillator solvent is triethylbenzene purified by treatment with activated alumina (coarse grain). The scintillator is 4 gm of diphenyloxazole (PPO) per liter of solvent with 0.01 gm of 2-(1-napthyl)-5-phenyloxazole (αNPO) per liter of solvent. Actually, toluene is a better solvent in that it is considerably more transparent than triethylbenzene, but at the time K-9 was built a coating was not available that was both a good reflector and resistant to toluene.

Circuit. The photomultiplier dynodes are fed from a single well-regulated high-voltage supply; the anodes are connected in parallel and feed into the input of a fast, high-gain pulse amplifier (Los Alamos model 503). The amplifier drives a fast counting-rate meter (Los Alamos model 800); counting rate is recorded on an Esterline-Angus recording milliammeter. For weak samples, a scaler is used; a discriminator with a variable upper gate can be introduced to improve signal-to-background ratio.

The photomultiplier circuit is conventional. Bleeder resistors between all dynodes are 0.47 megohms, with 1 megohm between photocathode (ground) and the first dynode. Anode resistors are 1 megohm. The last two dynodes have 0.005-μf by-pass capacitors to hold their potentials constant at high counting rates. Signals are taken out through 0.002-μf capacitors, the low-voltage sides of which are connected to the preamplifier input grid.† The bleeder network of each photomultiplier is decoupled from the common high-voltage supply by an *RC* filter, the resistor *R* of which also serves to equalize the gains of the photomultipliers.

Gain equalization is accomplished by a separate experiment. Each photomultiplier and its dynode network is connected to a supply voltage of +1,100 volts. A NaI(Tl) crystal, to which is fixed a Cs^{137} source, is coupled optically to each photocathode in turn. The output-pulse distribution is analyzed, and the value of *R* for each of the eight units is adjusted to give equal pulse heights for the Cs^{137} photopeak. A group of 20 photomultipliers was examined in this way, and eight were selected on the basis of minimum noise under conditions of equal gain.

Operating Characteristics

In determining operating characteristics of K-9, measurements were made of background, response to radium and radiothorium sources, effect of source position in the counter, and effect of shielding on background.

Tube noise, background. Response of K-9 to background and to gamma radiation as a function of discrimination level is plotted in Fig. 5. Output counting rates are very high compared to conventional scintillation counters because of the large mass of phosphor involved. At the standard K-9 operating condition (1,100-volt supply voltage, 10^4 gain, 10-volt bias level), about 6% of the background is due to tube noise.

Since the counting rates from K-9 are so high, the time required to achieve a given statistical accuracy is smaller than for conventional counters. Table 2 shows the results of background measurements on three successive days; 21 measurements of the time required to collect 50,000 background counts were made each day. Note that the observed fractional standard deviation of the mean is quite small (0.005), but it still is larger than the Poisson value by a factor of 5. This is no doubt due to the fact that the steep pulse-height spectrum of K-9 makes it more sensitive than usual to instability in the electronic gear. For 30-min counts on both sample and background, the limit of detection (3σ) is about 10 cps and the limit of measurement (to $\pm 10\%$) is 40 cps. As shown later, these numbers correspond to a radium content (assuming no radon exhalation) of 0.002 μg and 0.01 μg, respectively, in a beagle. For purposes of comparison, the maximum permissible burden for beagles (based on 0.1 μg for humans) would be 0.014 μg radium; the natural K^{40} content would be equivalent to about 0.002 μg Ra.

TABLE 2—Background Fluctuations in K-9

Date (1954)	Mean background (cps)	Fractional standard deviation		
		Mean (exp.)	Mean (theo.)	Single observation (exp.)
Jan 20	495	0.005	0.001	0.023
Jan 21	499	0.005	0.001	0.023
Jan 22	506	0.005	0.001	0.024

It is interesting that the background is still appreciable at high bias levels and that the pulse spectrum levels off at about 100 cps. These pulses that trip the discriminator at high bias levels are very large compared with ordinary pulses due to γ-rays, as can easily be seen on a triggered oscilloscope. They are due to high-energy cosmic ray particles (primarily μ-mesons) traversing the phosphor. In traversing K-9, these particles have a path length in the phosphor of roughly 10 in., compared with a path length of a few millimeters for the Compton recoil electrons produced by ordinary γ-rays ($h\nu = 1$ Mev). The ratio of these path lengths is about 50; assuming the average specific ionization to be roughly the same, the meson pulses should be larger than the γ-pulses by a factor of about 50. This is about what one observes with a triggered oscilloscope. The frequency of meson pulses can be calculated from the meson intensity at a 4,500-ft elevation (Salt Lake City), which is about 1 meson/cm²/min (*12*), and the cross-sectional area of K-9, which is 3,020 cm². Hence the meson flux through K-9 is about 50 mesons/sec, accounting for about half the observed counting rate at high discrimination levels. The rest is presumably due to high-energy electrons and photons.

Because of the leveling off of the integral background spectrum, use of an upper gate materially decreases background with only a small loss of signal; thus, a lower gate at 10 volts and an upper gate at 25 volts reduce the back-

* Gelva, manufactured by Shawinigan Resins, 350 Fifth Ave., New York 1, N. Y.

† There are advantages in an alternative arrangement in which all the anodes are connected together and a single anode resistor and output capacitor are used.

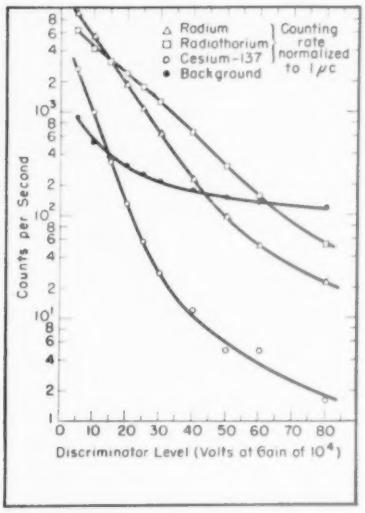

FIG. 5. Integral pulse-height spectra of background, Ra, RdTh and Cs^{137}

ground by a factor of 2 at the expense of only a 15% loss of radium signal.

Response to small Ra^{226} and Th^{228} sources. Figure 5 also shows the response of K-9 to a small radium (Ra^{226}) ampule placed at the geometrical center of K-9 as a function of discrimination level. At the standard operating point (10^4 gain, 10-volt lower gate), the counting efficiency of K-9 is 0.14 counts per radium α-ray. Note that the integral pulse-height spectrum of Fig. 6 shows little or no structure; this is not surprising because of the complex γ-ray spectrum of radium and its daughters (*13*) and since a large phosphor of low atomic number and nonuniform light collection efficiency makes about the worst spectrometer imaginable.

Figure 5 also shows the result of a similar experiment using a small source of radiothorium (Th^{228}) in equilibrium with its daughters. The integral pulse-height spectrum in this case is similar to that of radium (Ra^{226}) but shows more large pulses. This is due to the high average quantum energy (especially the 2.62-Mev γ-ray of ThC″) of the spectrum of the Th^{228} daughters. The Th^{228} counting efficiency is 0.11 counts per Th^{228} α-ray.

Response of each end separately. To get some idea of the effectiveness of each end of K-9 in seeing scintillations, a radium ampule shielded by two 1-in.-thick lead disks was arranged so as to produce a "disk" of radiation. The axis of this radiation "disk" was made to coincide with the K-9 axis. The counting rate, with the four photomultipliers at one end disconnected at a time, was measured as a function of axial position.

Results are shown in Fig. 6. The counting rate has its maximum value at about 4 in. from the sensitive end and decreases steadily to about half this value as the radiation source is moved down the axis to the end of K-9 containing the four disconnected photomultipliers. This is due to the decrease in light collection as the distance between scintillations and photomultipliers increases. The decreased output closer than 4 in. to the sensitive end is due to radiation not traversing the liquid; this effect would be absent if the "disk" of radiation had a small enough divergence angle.

These results were taken at an early stage when the photomultipliers were not properly equalized; this accounts

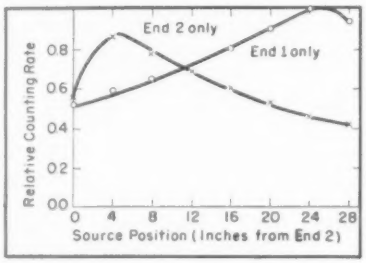

FIG. 6. Response of each end of K-9 to Ra disk source as function of axial position

for the asymmetry. However, they do show that when radium is the source, each end sees the opposite half of K-9 with such an efficiency that at the worst only about half the scintillations are lost.

Response as function of position. Further testing of K-9 was carried out with small radium and radiothorium ampules of negligible self-absorption, and with line sources of radium and radiothorium about 20 in. long. These measurements were made as a function of position inside K-9 both with and without a phantom. The phantom approximates an average beagle with respect to self-absorption; it is a cylinder of untempered Masonite $20\frac{3}{8}$ in. long and 6 in. in diameter, weighs 9.45 kg, and has a mean density of 1.01 gm/cm³. There are two holes $\frac{3}{4}$ in. in diameter penetrating the phantom; one runs down its axis ($r = 0$) and the other is parallel to it at $r = 1\frac{1}{2}$ in.

Figure 7 shows the response of K-9 to small radium and radiothorium sources as a function of their positions along the axis of the counter. The upper pair of curves are for the bare sources; the lower pair are for sources in the Masonite phantom. All curves are normalized to unity for the bare source centered in the counter.

The difference in the response of K-9 to sources of different quantum energy is quite marked. As expected from Fig. 6, counting efficiency for the γ-rays from the bare radium source is significantly reduced in the center (down 8%) because of the marginal light-collection efficiency at this point. (The central counting efficiency could be increased by lowering the discrimination level, but at the cost of considerable increase in background.) On the other hand, the radiothorium has a higher average quantum energy; hence the pulses are larger and there is very little change in counting rate over the major part of the volume occupied by the dog. This explanation of the central depression of the bare-source curve was verified by similar measurements with Cs^{137} ($h\nu$ = 0.66 Mev) and Co^{60} (average $h\nu$ = 1.25 Mev) γ-rays. The Cs^{137} source gave a central dip of 25% while the Co^{60} source gave only a 4% dip.

The different γ-ray spectra of radium and radiothorium also account for the shapes of the lower pair of curves of Fig. 7, obtained with sources inside the phantom. The radiothorium shows continued independence of position, while for the radium source the central

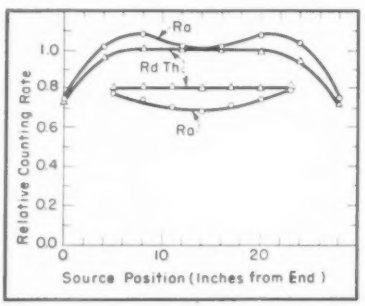

FIG. 7. Response of K-9 to Ra and RdTh sources as function of axial position (upper curves, no phantom; lower curves, with phantom)

dip is slightly increased. Note that phantom self-absorption is greater for radium than for radiothorium, as would be expected for the source of smaller average $h\nu$.

Table 3 shows the data taken with

TABLE 3—Response of K-9 to 20-In. Radium Line Source Averaged Over Angle

Radial source distance (in.)	*No phantom*	*Phantom centered*	*Phantom 1½ in. below center*
0	1.04	0.73	0.74
1½	1.05	0.77	0.79
3	1.10		

TABLE 4—Response of K-9 to 20-In. RdTh Line Source Averaged Over Angle

Radial source distance (in.)	*No phantom*	*Phantom centered*	*Phantom 1½ in. below center*
0	0.99	0.81	0.82
1½	1.00	0.83	0.85
3	1.01		

TABLE 5—Effect of Shielding on Integral Background of Los Alamos Annular Counter

Shielding	*cps*
None	630
2-in. Pb floor under counter	400
Floor + 1 wall (2 in. Pb)	330
Floor + 2 walls (2 in. Pb)	260
Floor + 3 walls (2 in. Pb)	220
Floor + 4 walls (2 in. Pb)	175
Floor + 4 walls (2 in. Pb) + roof (2 in. Pb)	90
Floor + 4 walls (2 in. Pb) + roof (4 in. Pb)	80
Floor + 4 walls (2 in. Pb) + roof (4 in. Pb) + 1½ in. Hg inside Pb	65
Floor + 4 walls (2 in. Pb) + roof (2 in. Pb) + 1½ in. Hg inside Pb	66
With upper gate	20
No Pb, 1½ in. Hg only	110

the line source of radium as a function of radial distance. The effect of rotating the off-axis line source around the counter axis is small (±2% or less) and is not shown. Counting rate increases a few per cent with radial distance. Note also that it makes little difference whether the phantom is centered or is lowered 1½ in. below the K-9 axis. Average transmission through the phantom is 72% ± 3%. Similar results are given in Table 4 for radiothorium. Average transmission for this source is 83% ± 2%.

Effect of shielding on background. When unshielded, K-9 background rate under standard operating conditions in Salt Lake City varied between 1,500 and 3,000 cps, depending on location. With a 4-ft-long cylindrical lead shield around K-9, of 1-in. wall thickness and with open ends, the background fell by a factor of 3. As noted previously, an additional factor of 2 is obtainable by using an upper gate.

Considerably more data have been obtained on the effectiveness of shielding on a similar annular counter at Los Alamos (7,300-ft elevation). This counter is about half the size of K-9. Table 5 summarizes the effect on the background of this counter of various amounts and types of shielding at such integral bias level that 1.5-Mev γ-rays are counted with 17% efficiency. The counter was located in the basement of a two-story reinforced concrete building, where there is some reduction in the hard-cosmic-ray background but a large increase in the local γ-ray background. Since this increase is due to relatively soft γ-rays, 2 in. of lead attenuate it considerably, as shown in Table 5. Note that an inner layer of Hg is effective in attenuating γ-rays due to contamination of the lead. Experience indicates lead is usually slightly radioactive. Once the local γ-ray background has been substantially reduced, an upper gate is very effective. Thus, the background is reduced by a factor of 3, while the K^{40} counting efficiency is reduced by only about 20%.

Measurements on dogs, rats. Measurements have been made in K-9 on beagles injected with radium and radiothorium and on rats injected with radium.

To date, a group of eight beagles varying in weight between 8.3 and 10.4 kg has been studied after injection with radiothorium. These dogs were measured immediately after injection and showed a self-absorption of 16 ± 2%; this number is in agreement with the phantom self-absorption of 17%. Self-absorption did not correlate with weight. Variation of counting rate with the dog's position in K-9 was negligible.

In the case of the dogs containing Ra^{226}, variation of counting rate with position in K-9 is also negligible. Radon exhalation, however, makes the measurement of self-absorption more difficult; experiments are underway to determine this quantity. In any event, it would be surprising if this number turned out much different from the result obtained with the phantom (28%). In the case of the complicated radium-radon elimination problem, the K-9 measurements and radon exhalation studies supplement one another. The former gives the amount of radon retained and the latter gives the amount of radon exhaled. Their sum gives the true radium content.

Retention studies with rats are being carried out at this laboratory. In this work the animals are sacrificed after about two weeks and bottled in formaldehyde in 1-quart Mason jars. Control animals are sacrificed soon after injection (before any excretion can occur) and bottled in the same way. When measured by placing the jars in K-9, the Ra^{226} samples showed a self-absorption of 18%.

* * *

We are indebted to Dr. Wright Langham of the Los Alamos Scientific Laboratory for his enthusiastic support of the development of this detector and for making possible its construction. Our information on the properties of the liquid scintillator systems was obtained from Dr. F. N. Hayes of the Los Alamos Scientific Laboratory, who also supplied the solutes used. Garth Westenskow and David Taysum of the University of Utah gave valuable assistance in resolving electronic and mechanical problems. Lon Sorenson and Richard Miller, University of Utah, gave valuable technical assistance and took most of the experimental data. This article is based on work done under the auspices of the U. S. Atomic Energy Commission.

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Failure and Disassembly of Los Alamos Fast Reactor

Here is how "Clementine" was torn down without contaminating area or endangering personnel. Reactor disassembly was necessary, early in 1953, after coolant became contaminated by a ruptured fuel element

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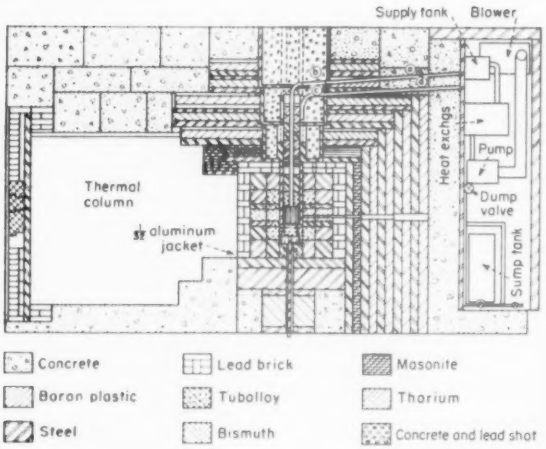
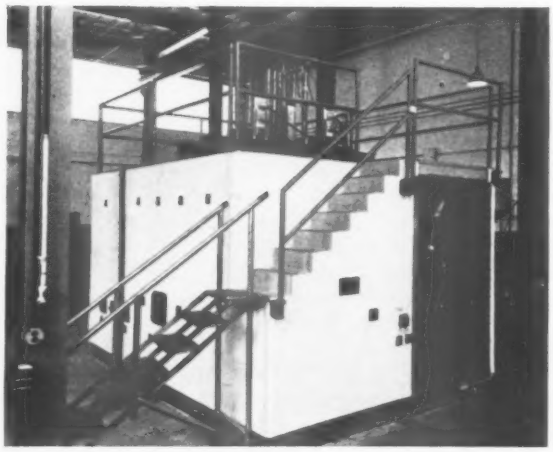




1 PLUTONIUM RODS AND NATURAL-URANIUM SPACER RODS, in 6-in. high array, form core, are contained in 6-in.-diameter mild-steel tank; mild-steel cage prevented rods from moving under coolant flow. Mercury coolant was pumped through bottom of pot, around rods, and out through top to external electromagnetic pump and heat-exchanger system. Evaporative water cooler connected to exchangers dissipated heat developed by reactor and pump. To sustain fast-neutron chain reaction, moderating materials were excluded from reactive region. Around fuel pot was 6-in.-thick natural-uranium reflector (silver-plated blocks arranged as cube); $\frac{1}{4}$-in. aluminum jacket, embedding cooling tubes, surrounded uranium cube; 6-in. steel, followed by 4-in. lead, surrounding jacketed uranium, produced 38-in. cube.

REACTOR SHIELD was alternate 3-in. layers of iron and Masonite and, later, iron and boron-impregnated plastic, for total 30-in. thickness on three sides of cube, and, finally, 18-in. heavy aggregate concrete. No shielding on cube's fourth side allowed for graphite thermal column. Top reactor shielding was removable laminated sections and heavy aggregate concrete blocks. Space above fuel inside steel pot was filled with reflecting and shielding plug conforming to materials in top shield. Over-all reactor dimensions were 11 × 15 × 9 ft high.

LINED, EXPERIMENTAL PORTS penetrated shield and reflector cube. Bismuth-block "window" allowed neutrons to reach thermal column. Since no material has sufficiently high fast-neutron-capture cross section to provide safe reactor control, control was accomplished by interchanging parts of uranium reflector with boron-10. Four control rods, made of B^{10} cylinder situated just over similar natural-uranium cylinder, operated in holes in uranium reflector, parallel and very close to pot; each rod produced reactivity change of ~0.4%, $\delta K/K$. Reflector "safety block," which could be made to seat against bottom of reactor pot or to drop 3 in., produced reactivity change of ~1.3%, $\delta K/K$. Negative reactivity temperature coefficient amounted to 2.6×10^{-5} $\delta K/K/^{\circ}C$. Since Xe poisoning presented no problem, reactor could be operated on any on-off schedule.

AT NOMINAL OPERATING POWER, 25 kw, fast-neutron fluxes were 10^{13} n sec cm^2 at innermost ends of experimental ports and 10^{9} n sec in well collimated external beams. Energy spectrum of these neutrons was similar to slightly degraded fission spectrum; at intermediate positions in ports, spectrum was greatly enriched in very-low-energy neutrons, especially near hydrogenous Masonite shielding. Thermal column provided fluxes of 10^{11}–10^{6} n sec cm^2. (Circled letters are cuts in coolant pipes, see Fig. 2.)

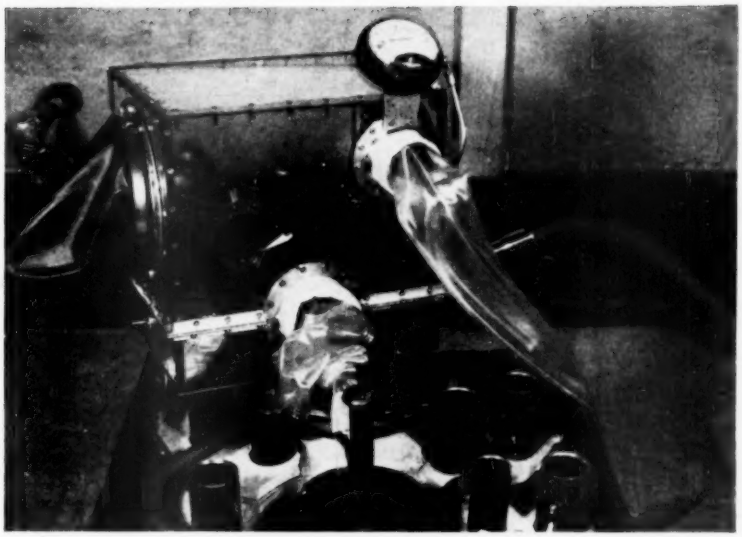
THE LOS ALAMOS FAST REACTOR ("Clementine"), a 25-kw fast-neutron research reactor, was brought to full operating power in March, 1949. After less than four year's operation, plutonium contamination of the mercury coolant necessitated its dismantlement.

During Clementine's useful lifetime, the reactor produced radioactive sources, supplied neutrons for fission-process experiments, permitted a survey of total neutron cross sections in the 3–12 Mev range for many elements, and enabled study of high-energy-neutron cataract production and fast-neutron elastic scattering.

Deterioration

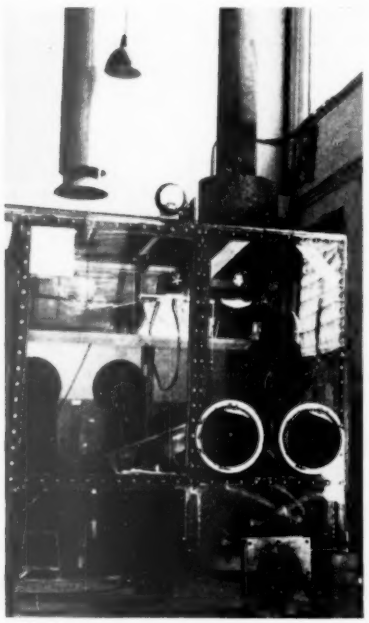
In March, 1950, α-activity in the mercury coolant led to the discovery of uranium and plutonium contamination. After a few weeks' delay to allow reduction of core radiation intensity, the fuel pot was opened. Careful inspection showed that one uranium spacer rod had ruptured; plutonium activity had evidently come from bred-in material. After the fuel rods had been leak tested, the reactor was reassembled with dummy steel cans replacing the uranium rods.

During the following year-and-a-half operation, it became increasingly evident that the uranium reflector pieces were undergoing changes. Corrosion



2 MOST DISASSEMBLING DONE IN DRYBOXES. It proceeded in the following way: (1) Mercury drained from external cooling-system parts; (2) coolant pipes cut at *a*, *b*, *c*, and *d*; (3) mercury removed from pot down to top level of fuel rods; (4) pot cut open at top and material filling space over fuel region removed; (5) fuel rods and dummy rods removed; (6) remaining mercury removed from pot; (7) control rods removed; (8) shield removed; (9) reflector cube, pot, and shielding cubes above reflector removed as unit; (10) concrete and steel pier supporting reflector cube removed.

SMALL 2-SECTION DRYBOXES for cutting mercury pipes (shown above) could be assembled and sealed around pipe; rubber gloves sealed to boxes permitted using ordinary tubing cutter. Negative pressure maintained by blower made any leaks inward. To prevent plutonium dissemination, wooden structure was built over top of reactor, sealed, and kept at negative pressure. "Plastic bag" technique was applied frequently—contaminated object was transferred between enclosures through vinyl bag sealed to both enclosures. After transfer, bag was twisted into tight rope and cut; two ends were sealed with tape. This technique was used to seal mercury pipe ends after sections had been removed and left in small dryboxes

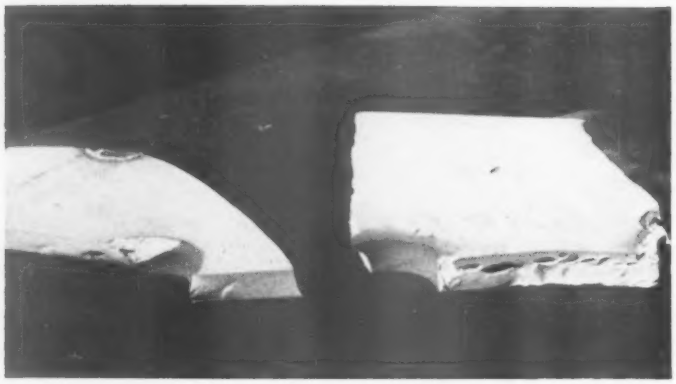


3 LARGE DRYBOX OVER TOP OF REACTOR and sealed to top of reactor pot with plastic bag was used for unloading fuel; weld closing pot was ground away with small hand grinder. Shielding and reflector plug were removed from pot, with overhead crane, through hole built into drybox and into large shielded container on drybox roof. Container, joined to drybox with large plastic bag, could be removed through door in roof of outer wooden structure.

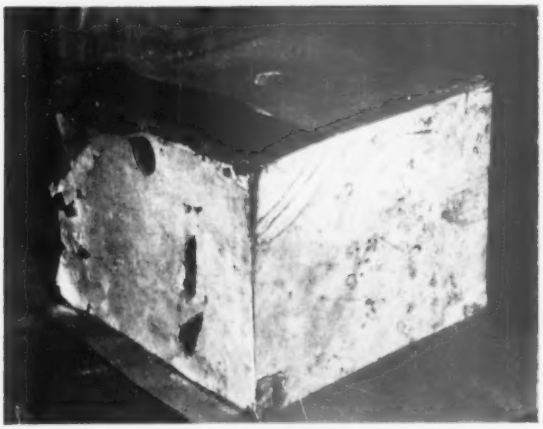
FUEL RODS WERE LOOSENED from steel cage in reactor core by a long manually operated grabbing tool. Small grabbing tool was lowered into pot by small crane inside dry box and coupled to loosened rod. Rod was lifted out of pot, over to left-hand side of drybox, and dropped into lead container joined to drybox floor by plastic bag; individual container was used for each rod. Chute was positioned so rod dropped off in transit would fall into reactor pot or into shield container. After unloading core, drybox was disjoined from pot and removed for disposal. Shield removal began after thermal column was unloaded.

RADIATION LEVEL INCREASED RAPIDLY after outside concrete layer had been removed and vertical laminated shield sections exposed. Contact levels at surfaces of four succeeding layers were: 0.030, 0.300, 1.5, and 4.5 r/hr. After last vertical steel section and small steel plates filling gaps on reflector's north side had been removed, level dropped to 0.060 r/hr. This sudden drop can be explained as follows: (1) Between aluminum jacket and steel blocks forming outside reflector layer was 4-in.-thick layer of lead, activation cross section of which is much less than iron's; (2) Masonite shielding slowed neutrons leaking through shield and greatly increased cross section for activating neighboring steel. Increased cross section also reduced number of slowed neutrons reaching reflector steel. Airborne alpha count became unexpectedly high when Masonite layer was approached. Alpha source was traced to lead turnings stuffed around port liners. Analysis showed decay was probably 138-day Po^{210}, undoubtedly formed from 0.1% bismuth impurity in lead turnings (especially in thermal flux in vicinity of Masonite)

4 RUPTURED FUEL ROD, mild-steel cased, is shown held up by electromagnet. To free it, cage segment was sawed out using hacksaw blade taped to end of long aluminum pipe



5 RADIATION DAMAGE to boron plastic and Masonite was pronounced at inner layers. In original state, plastic is smooth, white $\frac{3}{4}$-in.-thick sheets. Discoloration and distortion were marked adjacent to experimental holes. Masonite was not visibly damaged, but became extremely brittle



6 SILVER PLATING NEARLY DISAPPEARED from edges of uranium reflector blocks, exposing corrosion products on uranium surface. When lead layer surrounding reflector cube was exposed, radiation level was still low. After lead was removed, intensity 1 meter from steel blocks was 0.120 r/hr; after steel removal, intensity 1 meter from exposed uranium reflector blocks was 0.8 r/hr

7 REFLECTOR CUBE REMOVED with 2 top shielding cubes locked to it as a unit and carried away for storage; 2-in.-thick steel plates welded around reflector cube greatly reduced radiation level. Also shown is irradiated plastic material. Space inside U-shaped supporting pier had been stacked with boron-plastic sheets to prevent neutron leakage through channel underneath reactor containing safety-block-operating mechanism

products sifted down onto the safety-block actuating mechanism; the block finally failed to seat properly and at times would stick in its "up" position. Also, displacement of reflector blocks, presumably caused by abnormal metal growth or surface corrosion, impeded normal control-rod operation in their passageways through the reflector.

To correct these difficulties, the safety block was permanently held in its "up" position with a jack. Control-rod passageways were reamed out to a larger diameter to provide operating clearance. Increased control-rod diameter was also necessary to supply reactivity control lost through nonoperation of the safety block.

The reactor was restored to operating condition for only a few months. There was further evidence that the reflector blocks were shifting.

On December 24, 1952, the mercury coolant was again contaminated by α-activity. The only possible cause was release of plutonium from at least one fuel rod. Plutonium decay was quickly verified: 1–10 gm of plutonium were estimated to be free in the cooling system, producing a serious hazard. Further operation was cancelled.

Disassembly

The operating group spent the first three months of 1953 devising procedures and developing equipment for complete disassembly of the reactor.

Two biological hazards existed: radiation exposure and plutonium poisoning. Disassembly had to be devised to minimize these dangers and, if possible, to prevent radioactive contamination of the reactor housing.

The entire operation, shown in the accompanying illustrations, was done without exposing personnel to more than a small fraction of the tolerance radiation dose; only a barely detectable amount of plutonium escaped.

* * *

This article is based on a paper presented at the American Institute of Chemical Engineers' International Congress on Nuclear Engineering, Ann Arbor, Michigan, June 21, 1954.

Biological Applications of Tritium

This review describes how tritium has been applied as:

1 **Hydrogen tracer in biological systems. It provides a wider detection range than is possible with deuterium**

2 **Ionizing-radiation source. In an aqueous system, radiation field is uniform. Handling precautions are not serious**

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TRITIUM, already an important tool in biological studies, was first produced in 1939 by cyclotron bombardment of deuterium with deuterons (*1*). It has since been produced by a variety of other methods; for the past several years, it has been obtainable for experimental purposes from the AEC at a rather nominal cost.

The present review covers reports published through the year 1953. References to unclassified AEC documents have been included only when the information reported has not appeared subsequently in professional journals.

Pertinent properties of tritium are summarized in Table 1.

TABLE 1—Properties of Tritium

Mass of tritium atom (atomic wt. units)	3
Half-life	12.4 yr
Mode of radioactive decay	β, no γ
Product of radioactive decay	He^3
Maximum energy of β-particle	18 kev
Average energy of β-particle	5.7 kev

Tritium vs Deuterium

Applications of tritium in biological studies fall into two distinct categories. It can be employed as a tracer for hydrogen or as a source of ionizing radiation. As a tracer for hydrogen, tritium must compete with deuterium, the mass-2 stable hydrogen isotope.

Relative to deuterium, tritium possesses a number of advantages as well as some disadvantages. Perhaps its outstanding advantage is the greater concentration range over which it can be followed in living systems. For deuterium, there is a maximum range of about 10^3 between the largest concentration that shows no gross physiological effects and the smallest concentration in excess of normal deuterium abundance that can be accurately measured. For tritium, the corresponding concentration range is at least 10^5 and may be extended even further with elaborate counting procedures. Counting tritium, while presenting some difficulties due to the low-energy beta particle, is probably no more exacting than mass spectrographic or densitometric determination of deuterium.

Because of the large mass difference between tritium and ordinary hydrogen (protium), tritium exhibits rather large "isotope effects" in certain reactions. This disadvantage is shared, but to a somewhat lesser degree, by deuterium. The radioactivity of tritium necessitates certain precautions in its handling that are not required in the case of deuterium. Because of the nonpenetrating character of the tritium radiation, these precautions do not seriously limit the useful applications of the isotope.

As an experimental source of ionizing radiation, tritium-labeled water possesses unique advantages. It affords a uniform radiation field, which can be "built in" to any aqueous reaction system. The short range of its beta particle is usually a decided advantage in such applications, since it simplifies calculations of dosimetry and minimizes the hazard to the experimenter.

METHODS EMPLOYED IN DETECTING TRITIUM

Methods employed in biological studies with tritium differ from those commonly employed with other isotopes, principally in regard to detection procedures. Tritium is unique among the more widely employed beta-emitting isotopes in the very weak energy of its radiation, which necessitates

TABLE 2 Counting Instruments Employed for Tritium

Type of Instrument	*Chemical nature of sample counted and references*
Ionization chamber	Hydrogen gas (*2–4*), acetylene gas (*5*)
Geiger or proportional counters (for gaseous samples)	Water vapor (*6*), hydrogen gas (*7–15*), methane gas (*16, 17*), butane gas (*18*)
Liquid-scintillator counter	Organic compound soluble in scintillator solution, or dilute solution of water in alcohol (*19–23*)
Windowless flow counter (for solid samples)	Infinitely thick solid sample (*24*), NH_4Cl (*25*), paper chromatograms (*26*)

specialized counting instruments and procedures. Lack of suitable counting instruments, or lack of experience in using these instruments, has no doubt been largely responsible for the limited use of tritium in biological studies.

Table 2 indicates the variety of counting instruments now available and gives some impression of their adaptability to specific problems.

Sample Preparation

As indicated in Table 2, solid samples containing tritium can be counted under certain circumstances where high sensitivity is not required; liquid-scintillator counters accept samples of certain organic compounds soluble in the scintillator solution, or water samples in small quantities.

Gaseous samples. In most applications, however, it has been necessary to combust the biological material, converting tritium to the oxide, which is in turn converted to some gas suitable for filling the ionization chamber, G-M, or proportional counter. Payne, *et al.*, (*27*) and Glascock (*28*) have described procedures specifically designed for quantitative combustion of tritium-labeled organic material. Wilzbach, *et al.*, (*29*) have described an ingenious method, employing zinc and nickelic oxide in a high-temperature sealed-tube reaction that, in one step, converts the hydrogen of organic material to a hydrogen-methane mixture that is suitable for direct introduction to an ionization chamber or G-M tube.

The variety of gaseous forms in which tritium has been counted is indicated by the listings in Table 2.

Autoradiography. Several workers (*30–32*) have successfully employed autoradiographic tritium detection in tissue preparation. Because the average β-particle from tritium traverses less than 1 μ in photographic emulsion, it is ideally suited for intercellular or intracellular localization of activity. Resolution of less than 1 μ is readily discernible (*31*). Autoradiography has been used for quantitatively estimating tritium (*31, 33*).

TRITIUM AS HYDROGEN TRACER

Tritium, as a hydrogen tracer, has been used in the gaseous state (mainly to study its radiation hazard), as the oxide, and with labeled organic molecules. In these applications, the "isotope effect" must be considered.

"Isotope Effect" Problem

From theoretical considerations, it is clear that hydrogen isotopes differ in their reaction rates in specific reactions (*34*). Such isotope effects have been observed with deuterium in various chemical reactions (*35*). It has been generally assumed, however, that for the complex system of equilibria involved in a living organism no significant over-all isotope effects would be anticipated. This conclusion is supported by many studies of the deuterium/protium ratio in living and nonliving materials of all sorts, which usually have indicated that this ratio is essentially constant (*36, 37*).

Tritium/deuterium ratio. The availability of deuterium and tritium as hydrogen tracers has led to studying the comparative behavior of hydrogen isotopes in living systems. These studies have usually involved administering tritium- and deuterium-labeled water to animals, followed by determination of the tritium/deuterium ratio in various body constituents. Glascock, *et al.*, (*38*) have reported a consistent 20% decrease in the tritium/deuterium ratio in mammary fat from lactating rats and in the body fat of the young that were suckling during administration of labeled water. Larger but less consistent effects were reported in an earlier communication from these workers (*39*).

In a similar study, Eidinoff, *et al.*, (*40*) reported preferential incorporation of approximately 8 and 18% deuterium in liver glycogen and liver fatty acids, respectively, of rats. In experiments in which the labeled water was administered over a period of 5 weeks, and animals sacrificed over a period of 2 months, Thompson and Ballou (*41, 42*) noted preferential incorporation of deuterium by 6–7% in the muscle, fat, and brain of rats. No significant isotope effect was noted in body water, liver, pelt, or residual carcass; the tritium/deuterium ratio remained constant in all tissues following incorporation.

Weinberger and Porter (*43, 44*) have studied incorporation of all three hydrogen isotopes by algae grown in media containing no source of hydrogen other than water. Deuterium was incorporated at about half the rate for protium, and tritium at about 90% of the rate for deuterium. The isotope effect was found to vary significantly in different chemical fractions from the algae (*44*). In studies with tritium- and deuterium-labeled methanol, Verly, *et al.*, (*45*) observed a greater retention of the carbon-tritium bond in the utilization of the methyl group of methanol in the biosynthesis of the labile methyl group.

According to these results, tritium and deuterium may be expected under certain conditions to show significant isotope effects in their metabolism. Experiments utilizing them as tracers should be designed and interpreted with this fact in mind. The largest effects probably will be observed in short-term studies of rather specific biochemical reactions in which kinetic effects in the rupture of carbon-hydrogen bonds may be observed. In chronic studies, significant isotope effects would seem to be incompatible with the generally observed constancy of the deuterium/protium ratio in natural materials of biological origin. Our present knowledge of hydrogen isotope effects in the over-all metabolic

reactions of a living organism is clearly inadequate for precise prediction.

Gaseous-Tritium Studies

Biological investigations employing gaseous tritium are rather limited in number and have mostly been directed toward hazards of handling.

Pinson and Anderson (*46*) exposed rats to a tritium-gas atmosphere for periods up to 134 hr. Less than 0.1% of the total inspired tritium was retained in the animals as tritium oxide. In similar studies on two human subjects, 0.004% of the inhaled tritium was retained as tritium oxide (*46*). Similar findings on rats were reported by Smith, *et al.*, (*47*). In these studies, intestinal-tract bacterial flora was implicated as probably the most important agent in converting tritium to the oxide. Smith, *et al.*, (*48*) have also followed tritium-gas concentration in the blood of rats, during and following exposure. Except for the small fraction converted to oxide, tritium is rapidly lost from the animal on cessation of exposure. In addition to tritium retained as oxide, small quantities are incorporated into various tissue compounds. There is some indication that this incorporation follows a different pattern when animals are exposed to tritium gas than it does when they are exposed to tritium oxide (*48*).

Skin permeability. DeLong, *et al.*, (*49*) have compared the rate of passage of tritium gas through excised mouse, rat, and human skin. The rate through human skin is about $^1/_3$ of that through rat skin. The permeability of skin to tritium gas has been studied in intact rats by Smith, *et al.*, (*48*). Retention as tritium oxide following total-body skin exposure amounted to about $^1/_{40}$ of the retention following pulmonary exposure to the same atmosphere.

Gaseous tritium has been employed to determine the hydrogen-fixing abilities of microorganisms (*50*). By virtue of tritium's detectability at very low concentrations, these bacteriological reactions can be studied at physiological hydrogen concentrations. The ability of green plant leaves to metabolize atmospheric tritium has also been investigated (*51*).

Tritium-Oxide Studies

One of the most obvious tracer applications of tritium oxide is in studying body water pools and the kinetics of water distribution. Previous reviews have appeared on earlier work (*52, 53*).

Pace, *et al.*, (*6*) first employed tritium-oxide dilution for determining total body water. Their experiments, limited to two rabbits and one man, were handicapped by the low specific activity of the tritium available at that time. Prentice, *et al.*, (*54*) reported much more extensive studies, including body-water determinations on 20 normal and 37 diseased individuals. Values for total body water by the tritium-oxide-dilution method were shown to be comparable to those obtained with deuterium oxide, and 2–4% lower than those obtained with antipyrine. Deuterium or tritium exchange with labile hydrogen of organic molecules accounts for this discrepancy. These studies have since been extended to include 100 normal individuals (*55*). Body dilution volumes for tritium oxide in man averaging 62.2% were reported by Pinson, *et al.*, (*56*). Using the tritium-oxide-dilution method, Picon-Reategui, *et al.*, (*57*) have studied the effect of altitude on body water content of rats. At simulated altitudes of 15,000 ft, 20% of body water was lost within a week.

Body-water turnover. A number of investigators have studied the dynamics of body-water turnover with tritium-oxide tracer. The biological half-life of body water in nine human subjects ranged from 9.3 to 14 days under normal conditions of fluid intake; forcing fluids shortened it to as little as 2.4 days (*46*). Body-water half-life determinations in experimental animals include 1.1 days (*5*) and 1.5–2.0 days (*46, 58*) for the mouse; 3.3 days (*59*) and 3–5 days (*46*) for the rat; and 5.2 days (*60*) for the sheep.

Prentice, *et al.*, (*61*) studied the circulation of ascitic fluid in six patients using tritium-labeled water and found that 40–80% of the ascitic fluid leaves the peritoneal cavity per hour.

Tritium-oxide intake. The possible routes of tritium-oxide entry into the body have been extensively studied, primarily related to hazard control.

Essentially all inhaled tritium oxide is retained and rapidly mixed with body fluids. This has been demonstrated in mice (*62*), rats (*46*), and humans (*63*). In the human studies, tritium oxide exhaled during the 5-min exposure period amounted to less than 2% of the quantity inhaled. The tritium-oxide concentration of exhaled water vapor reached equilibrium with body water in 30 min, and the tritium-oxide level in venous blood attained an equilibrium value in 80 min.

Ingested tritium oxide is completely absorbed from the gastrointestinal tract, appearing in venous blood within 2–9 min following ingestion, reaching a maximum concentration in about 45 min and decreasing slightly to an equilibrium level at about $2^1/_2$ hr (*56*).

By means of tritium-labeled water, inward passage of water through skin exposed to water vapor was unequivocally demonstrated for the first time (*64*). The tritium-oxide absorption rate through the skin has been rather thoroughly investigated in mice and rats (*65, 66*), on limited skin areas in the human (*52, 65–67*), and for total-body exposure of a human (*65, 66*). Percutaneous tritium-oxide absorption in rats was shown to be independent of total-water vapor pressure. The quantity of tritium oxide absorbed percutaneously by man was shown to be of comparable magnitude to the quantity that would be absorbed via the lungs. The percutaneous absorption rate increases by a factor of 2–4 over the first 10 or 20 min of exposure, probably indicating a holdup of absorbed water vapor in the horny outer skin layer.

Tritium-oxide body distribution. By whatever process tritium oxide is administered to an animal, it appears to be distributed rapidly and uniformly throughout the body fluids. Tritium-oxide concentration in tissue water did not vary among 13 different organs and tissues removed from rats previously injected with tritium oxide (*59*). In experiments on humans, the tritium-oxide concentration in water from sweat, insensible perspiration, expired vapor, sputum, urine, blood, gastric juice, and seminal fluid was identical within experimental limits (*46, 68*).

Tritium incorporation into organic compounds of the body upon exposing an organism to tritium oxide has been studied in a number of experiments. After administering tritium oxide to mice over a 2-week period, Thompson (*5*) found 0.5–1.0% of the tritium in the organically bound state. Similar experiments with mice have been reported by Pinson, *et al.*, (*58*). In an experiment with rats, involving only a single tritium-oxide injection, about 1.3% of the administered tritium was in the organically bound state 6 days after injection (*59*); organically bound tritium was determined separately in

13 different organs and tissues. The highest concentration of bound tritium, one day following tritium-oxide administration, was found in the liver, where the concentration was 20 times that in the muscle. By the sixth day following tritium-oxide administration, the concentration of bound tritium in all tissues studied had become much more uniform, varying over a four-fold range with the highest concentration in liver and the lowest in bone.

In experiments in which rats were chronically exposed to a constant tritium-oxide environment from conception to the age of 6 months, 20–25% of the hydrogen of most tissues was derived from body water (*69*). In brain, nearly 40% of the hydrogen was derived from body water. Pinson, *et al.*, (*70*) determined tritium concentration in skin and fat organic components of a human exposed to varying tritium-oxide concentrations over an 8-month period.

Tritium distribution in algae (*32, 43, 44*), yeast (*30, 31*), and protozoa (*30–32*) has been studied following growth of these organisms in a medium containing tritium oxide. Balmain, *et al.*, demonstrated insulin stimulation of *in vitro* fat synthesis by mammary-tissue slices, using tritium oxide in the incubation medium and measuring its incorporation in fat (*71*).

In an early study, Norris, *et al.*, (*72*) studied tritium incorporation into algae chlorophyll growing in media containing tritium oxide. Cline (*51*) has reported on the uptake of tritium oxide, and tritium incorporation into organic constituents of bean plants growing in nutrient solution containing tritium oxide.

Compounds other than Oxide

Deuterium-labeled organic molecules have been widely employed in biological studies; tritium-labeled molecules should be similarly useful. Tritium-labeled molecules for such purposes can be prepared by laboratory synthesis, by synthesis in living organisms from which the labeled compound is subsequently isolated, or by synthesis in the organism in which their subsequent fate is to be studied. The latter method has seen the greatest application to date.

Tissue retention of tritium. The retention of total tritium-labeled organic material in the mouse was studied by Thompson for 160 days after exposing the animals to tritium oxide (*5*). At the end of this period, tritium was still readily detectable in the organic material, but had long since been reduced below measurable quantities in body water. The animals were losing an appreciable fraction of the retained tritium with an approximate biological half-life of 90 days.

Retention of tritium-labeled organic materials in various rat tissues and organs has been similarly studied; results indicate substantial fractions having long biological half-lives in nearly all tissues (*59*). Various lipid and protein fractions have been isolated from rats whose organic constituents had previously been labeled with tritium (*73*). The changes in tritium concentration with time in these fractions demonstrate the widespread distribution of relatively metabolically inert materials in the organism. Studies of Thompson and Ballou (*69*) on retention of organically bound tritium in rats following chronic exposure to tritium oxide indicate that these undynamic fractions constitute the major fraction of the organic constituents of most tissues.

These studies of bound-tritium retention illustrate rather well tritium's superiority over deuterium in investigations of this sort. By virtue of the greater analytical sensitivity in tritium studies, fractions with slow turnover rates, and consequent low levels of isotope incorporation, are easily studied with tritium, whereas they had been overlooked in deuterium studies.

Studies of labeled compounds. A relatively small number of studies utilizing specific tritium-labeled compounds have been reported. Synthesis of a considerable number of such compounds has been reported, however, and results of biological studies employing these compounds may be soon forthcoming. Gurin and Delluva (*15*) demonstrated phenylalanine-to-adrenalin conversion in the rat by feeding tritium-labeled phenylalanine and isolating tritium-labeled adrenalin. Biggs, Kritchevsky, and Kirk have conducted several studies employing tritium-labeled cholesterol. Cholesterol labeled with both tritium and carbon-14 was fed to a rabbit; cholesterol isolated from various sources showed a constant T/C^{14} ratio, thus demonstrating the firmness of the tritium label under the conditions employed (*74*). Differences in cholesterol metabolism were demonstrated between normal and hypercholesterolemic rabbits (*75*). Labeled-cholesterol distribution was studied in rats, and its metabolic utilization for synthesis of fatty acids and glycogen was demonstrated (*76*). Balmain, *et al.*, (*77*) have employed acetate labeled with both tritium and carbon-13, in conjunction with carbon-14-labeled glucose, to study the relative utilization of glucose and acetate carbon for lipogenesis by mammary gland slices.

TRITIUM AS SOURCE OF IONIZING RADIATION

Relatively few toxicity studies of the classical LD-50 type have been reported for tritium. This is perhaps largely due to the relative certainty of predictions of toxic effects, based on the well established isotope distribution pattern, and due also to absence of any indication of unusual biological effectiveness of tritium radiation. A 30-day median lethal dose of about 1 mc/gm body weight was estimated with CF-1 female mice (*78*). Jennings and Brues (*79*) reported a median lethal radiation dosage from tritium oxide, administered chronically to rats over a two-month period, of 57–77 rep/day. The mean accumulated dosages to death were 3,000–3,700 rep.

Biological effectiveness of H^3 radiation. The relative biological effectiveness (RBE) of tritium radiation has been studied by a number of workers, employing various biological systems. These studies have quite consistently indicated that the RBE is somewhat greater than that for more energetic radiation, but only by a factor of two at the most.

Getzendaner, *et al.*, (*80*) have compared the effectiveness of tritium, phosphorus-32, and sulfur-35 in inhibiting the growth of *Lactobacillus casei*, with a resulting average tritium RBE, relative to the other radioisotope studied, of 1.7. Powers and Shefner (*81*) compared the effects of tritium, strontium-89-90, yttrium-90, and X-rays on lethal-mutation induction in *Paramecium aurelia*. Tritium appeared to be slightly less effective than the more energetic beta emitters at similar dose levels. Studies of the effect of tritium on mouse tumor implants (*82*) and chick-embryo muscle fibroblasts (*83, 84*), *in vitro*, indicate no unusual RBE for tritium.

Comparing tritium with an external gamma emitter, cobalt-60, for their effect in depressing iron-59 uptake in rats, Furchner, *et al.*, (*85*) obtained a tritium RBE of 1.59. Worman, *et al.*, (*86*) using spleen and thymus weight loss in mice as an index of radiation effect, found an RBE for tritium beta radiation of approximately 1.4 compared with external radium gamma irradiation.

Permissible exposure. Maximum permissible limits for exposure to tritium have been suggested by several official groups (*87–89*). Because of the difficulty in distinguishing between tritium-gas and tritium-oxide contamination in routine monitoring procedures, all calculations of maximum permissible limits have been based on tritium oxide, the more biologically hazardous of the two forms.

The most recent suggested values for permissible continuous-exposure limits are: total body burden, 10^4 μc; concentration in water, 0.2 μc/ml; concentration in air, 2×10^{-5} μc/ml (*89*).

Radiation-Damage Mechanism

The most extensive studies with tritium in this field are those of Porter, *et al.*, on the tritium-radiation effect on growth and metabolism of the algae, *Chlorella pyrenoidosa*. Gross effects on growth and morphology were determined under various conditions (*90, 91*); radiation effects on specific metabolic processes were studied by following C^{14} incorporation into various compound fractions, subsequent to algae irradiation by tritium (*92*).

Getzendaner and Fujihara (*93*) have investigated the destruction of riboflavin, biotin, and folic acid in very dilute aqueous solutions containing tritium oxide, using microbiological assay procedures to follow the time course of destruction.

FUTURE PROSPECTS FOR BIOLOGICAL APPLICATION

With the ready availability of high-specific-activity tritium, and the development of simplified counting procedures adaptable to a wide variety of sample types, tritium use in biological studies should rapidly expand. It may replace deuterium as a tracer in many applications, and may be used to particular advantage in conjunction with deuterium in experiments requiring two different hydrogen labels. The unique advantages of tritium in certain autoradiographic applications and as an *in vivo* source of uniform radiation, should insure an expanded use of the isotope in these fields.

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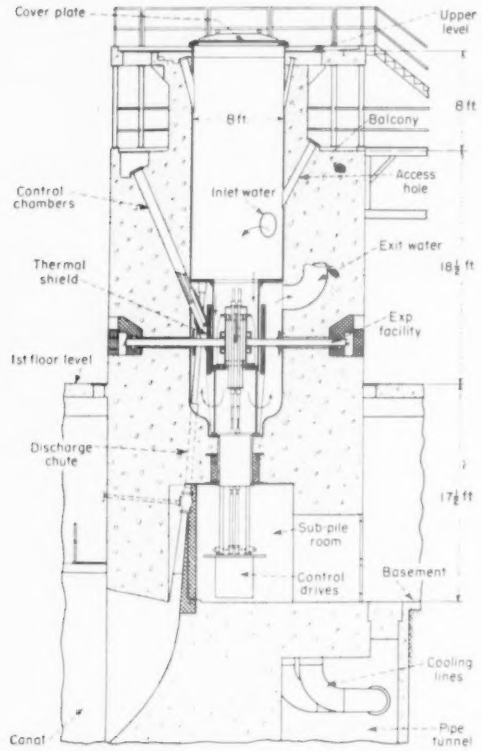
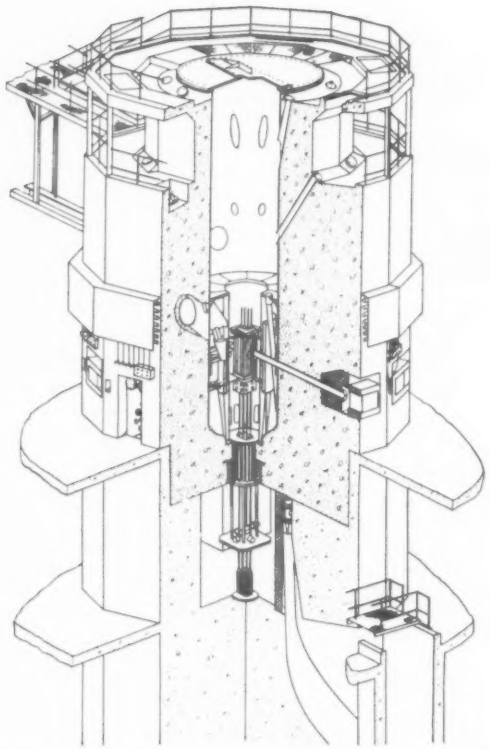
Design for a High-Performance

Designed for highest thermal flux per dollar invested, 10-Mw reactor costing $2,500,000 provides 10^{14}-n/cm^2/sec thermal flux. Enriched-uranium, light-water cooled and moderated system devotes maximum space to experimental facilities

Reactor Construction





1 REACTOR STRUCTURE consists of aluminum housing to direct coolant flow, stainless-steel support tank, bottom plug and control drives, all referenced from machined surface at bottom of large tank; 8-ft-diameter tank is 31 ft high. Sleeves at upper levels house tubes for core insertions. Top cover plate can be altered for vertical access into core. Fission chamber, motor driven through bottom plug, is located below fuel section in reactor start-up position.

LEAD THERMAL SHIELD, stainless-steel clad, prevents excessive temperature rise and thermal stress in neighboring concrete. Shield is cooled by upward flow of water. Six-inch-diameter discharge chute extends from baffle plate of reactor tank through shield to region outside of subpile room; handling tool and valve operated on south face of reactor foundation allow for disposal of fuel assemblies, etc., to storage canal. Second chute outside of large tank extends from top of structure to canal.

BIOLOGICAL SHIELD provides for maximum radiation level of 0.1 tolerance at 30 Mw. At beam-hole level it consists of 3 ft of water and 7 of barytes concrete; below reactor, 6 ft of water and 4 of iron shot in bottom plug. Due to bottom-plug openings, radiation level is higher in subpile room; latter is not continuously inhabited during operation. With 20 ft of water above reactor, radiation is above tolerance; shielding can be added to cover plate.

SMALL COVER PLATE on tank is removed for normal refueling and servicing; large cover, for major repair, is easily altered for additional access holes. Since water system is at atmospheric pressure at low power levels, it is possible to operate without top cover plate. Grating on upper level can be removed for inserting experiments through sleeves in upper part of large tank. Drain lines in this recess confine accidental tank overflows and other contaminations

Research Reactor

By JOSEPH P. GILL
Oak Ridge National Laboratory
Oak Ridge, Tennessee

THE "HIGH PERFORMANCE RESEARCH REACTOR," a heterogeneous reactor with an initial 10-Mw power level, has been designed as a permanent research facility at ORNL.

Since the core—enriched uranium, light-water cooled and moderated—is similar to several in operation, no critical experiments were required to predict fuel loadings, flux distributions and operating conditions. The reflector is a relatively thin beryllium-metal layer backed by a thick layer of water.

Since the heterogeneous core has proved sound for research purposes, it is used in a majority of currently planned research reactors and will probably form the nucleus of design for many years to come. Therefore, this research-reactor design, rather than improving core or control design, is seeking engineering improvements that will substantially reduce installation cost and provide a flexible machine.

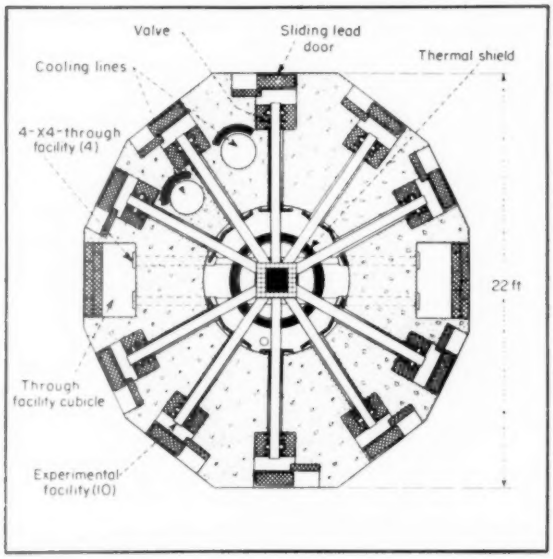
The major contribution of this design is its provision for the maximum number of high-flux experimental regions. Location of the drive and release mechanisms for safety and control rods below the reactor core allows installation of vertical insertions into higher-flux core regions. Control operation from below has proved satisfactory under simulated operating conditions.

The building is a mill-type structure, $73 \times 84 \times 70$ ft, with a $28 \times 84 \times 20$ ft low section; a basement extends under the entire structure. Framing is structural steel with either corrugated, asbestos-insulated interior panels or insulated metal siding. Floors, foundations, reactor base, basement and canal walls are reinforced concrete.

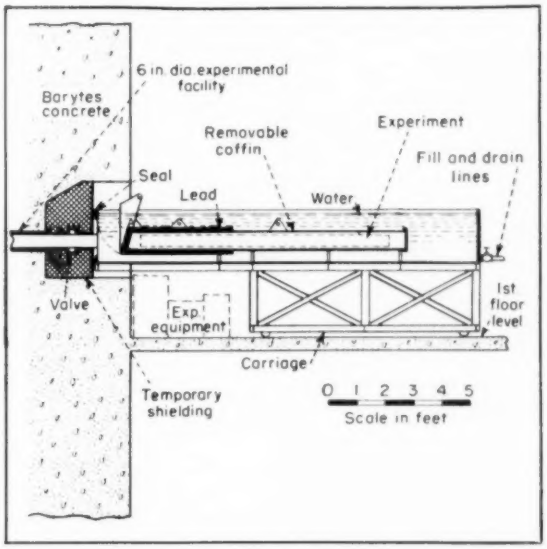
The basement area provides for pile foundation, subpile room, and transfer and storage canals. The entire area is serviced by a 5-ton monorail system. Ceiling height is 17 ft.

The first-floor area, constituting the main experimental area, houses the reactor structure and plug-disassembly

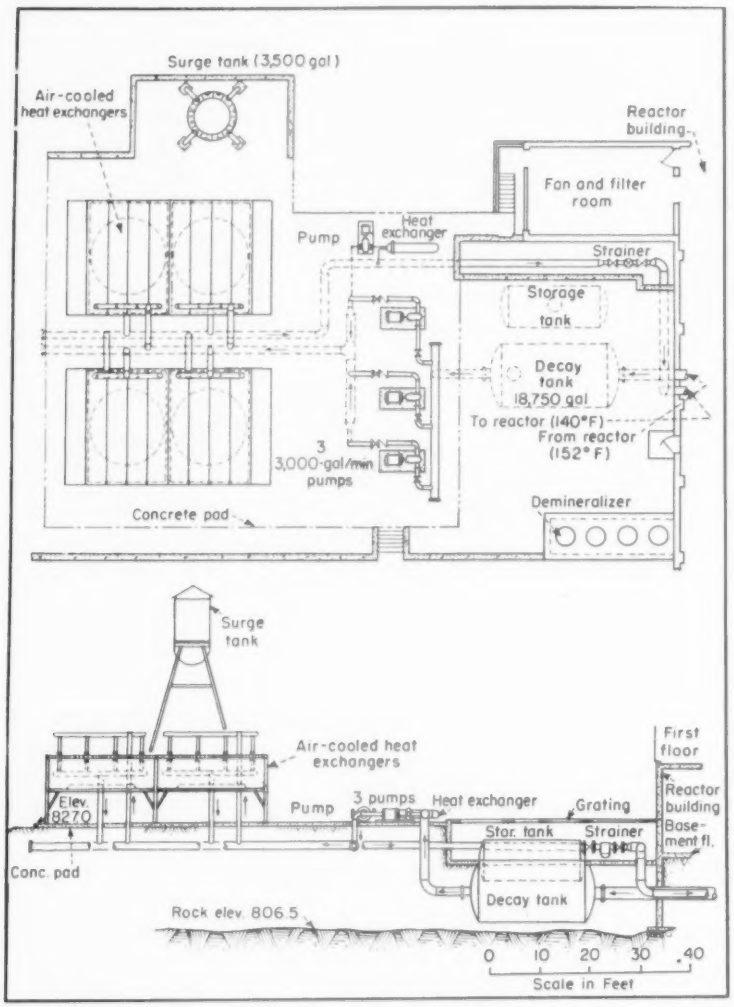
Experimental Facilities



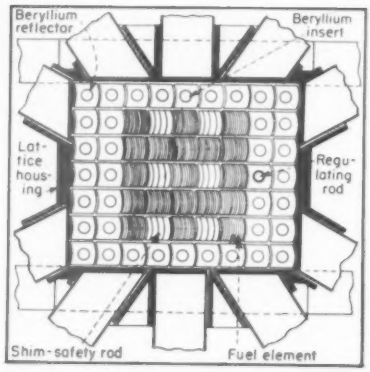
2 MAIN EXPERIMENTAL FACILITIES consist of ten 6-in.-diameter beam holes, located in one plane at centerline of reactor, and four square through facilities, located above and below beam holes on east and west faces of lattice. One of these holes would be used for series of rabbit-tube installations. A variation of experimental-facility arrangement could be elimination of two beam holes and one side of through facilities in favor of a thermal column, or experiments requiring large volumes of equipment located close to reactor source



3 TYPICAL EXPERIMENTAL INSTALLATION utilizes water trough bolted to beam-hole liner flange to allow plug removal under water into coffin. Commercial sliding-disk valve, operated remotely, is closed after removing plug and flooding liner with water for sufficient shut-down shielding. Stainless-steel liner in concrete, aluminum liner extending from cubicle to core and tube housing for experiment are commercial pipe and tubing with liberal clearances. Annulus filled with water for shielding during operation is considered advantage over usual expensive stepped plug and liner



4 COOLING SYSTEM is similar to that used on LITR (ORNL). Water leaves reactor tank, passes to shielded hold-up tank (3-min delay permits short-lived-activity decay), is pumped to fin-type air-cooled heat exchangers, and recirculated through reactor. Water quality is maintained by resin-bed demineralizers. System capacity is 35,000 gal with 5,500 gal/min circulating rate. With exception of cast-iron pumps and some fittings, aluminum is used throughout



5 REACTOR-CORE LATTICE consists of aluminum-clad, Al-U-alloy curved plate assemblies. Beryllium reflector pieces, same shape as fuel assemblies, provide 7 or 15 cm of reflector in lattice. Movable shim-safety rod assemblies in six core positions provide for additional fuel during burn-up or cadmium poisoning. Fast-acting cadmium regulating rod moves through one reflector piece

TABLE 1—Neutron Flux Data*

Operating power (kw)	10,000
U^{235} in core (gm)	3,300
Average thermal flux	7.2×10^{13}
Max. thermal flux in core	1.3×10^{14}
Max. thermal flux in reflector	1.6×10^{14}
Max. fast flux† in core	4×10^{13}
Max. fast flux† at surface of core	3×10^{13}
Thermal flux at face of beam holes terminating at core surface	6×10^{13}
Fast flux at face of beam holes terminating at core surface	3×10^{13}
Thermal flux at face of beam hole separated from core by one reflector piece	6×10^{13}
Fast flux at face of beam hole separated from core by one reflector piece	6×10^{13}

* Flux given as $n/cm^2/sec$.
† Refers to neutrons greater than 1 Mev.

TABLE 2—Estimated Reactor Cost

Reactor building	$ 425,000
Reactor structure	305,000
Reactor utilities	63,000
Reactor components	419,000
Reactor instrumentation	157,000
Reactor cooling system	347,000
Reactor auxiliary equipment	45,000
Overhead	350,000
Engineering	275,000
Contingencies	114,000
Total estimated project cost	$2,500,000

cell. The high portion of the experimental area is serviced by a 20-ton bridge crane with 55-ft vertical hook travel. Removable hatches over two sections of the floor provide crane service to canals and basement.

The second-floor area, principally the building's low section, provides space for control room, equipment room, and offices. A combination bridge and service channel allows access from the second floor to the top level of the reactor.

Flux data and estimated costs are given in Tables 1 and 2, respectively. Construction costs would probably be higher at locations other than Oak Ridge, where facilities such as services, laboratory space, disassembly cells and equipment already exist.

* * *

This article is based on a paper presented at the American Institute of Chemical Engineers' International Congress on Nuclear Engineering, Ann Arbor, Michigan, June 21, 1954.

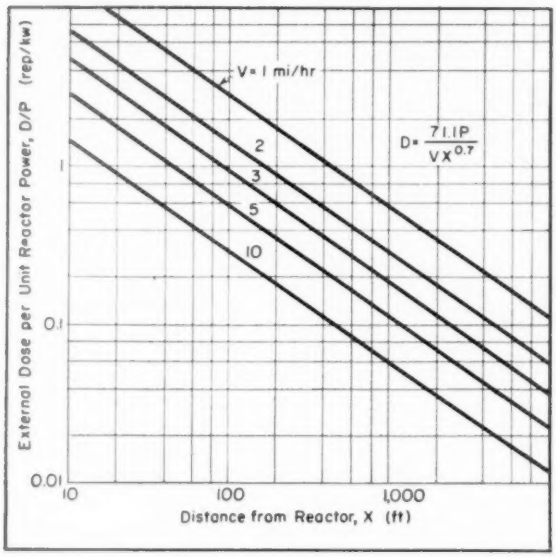


FIG. 1. Maximum *external* dose under *inversion* conditions

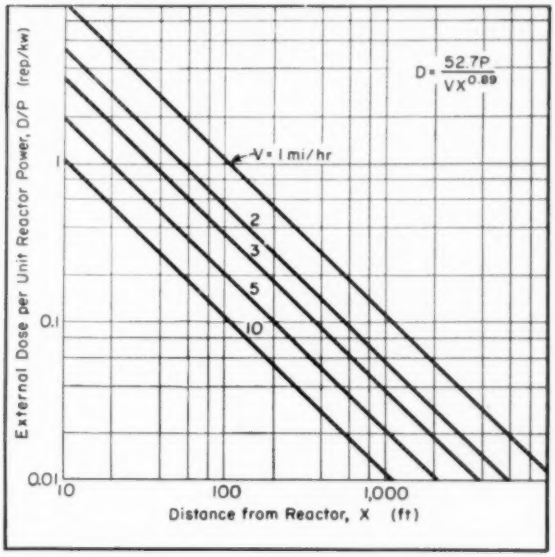


FIG. 2. Maximum *external* dose under *lapse* conditions

Evaluating Reactor Hazards from Airborne Fission Products . . .

. . . involves estimating: 1, contaminant concentration downwind from the source; 2, external doses; 3, inhalation doses; 4, doses from fallout

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MAXIMUM POSSIBLE HAZARD from a nuclear incident in which all of a reactor's radioactive contaminants are dispersed into the air can be evaluated by methods presented in this article. Possible results of a total catastrophe should be considered even though it is standard practice to design reactors, their auxiliary equipment, experiments, and operating procedures so that damaging reactivities can not be introduced into the reactor even if equipment should fail or the experimenter should make a serious error.

The maximum *credible* accident with a given type of reactor is somewhat less than the maximum *possible* accident and must be evaluated for the particular design under consideration.

1. Contaminant Concentration

The total possible accident is represented by the instantaneous release of all the fission products to form a radioactive cloud above the reactor building. The problem of how contaminants are carried from their source by winds has been studied by meteorologists in the Chemical Warfare Service and in Atomic Energy Commission laboratories (particularly Brookhaven National Laboratory). The best expression for calculating contaminant concentration downwind from the source has been developed by Sutton (*1*). This formula describes concentration of contaminants as a Gaussian function of distance measured from the cloud center and as a function of the distance downwind from the source of contamination. For concentration from an instantaneous point source, Sutton's equation can be expressed as

$$\chi(x,y,z,t) = (2Q/[\pi^{3/2}C_xC_yC_z(ut)^{3/2(2-n)}]) \times \exp\left[(ut)^{n-2}\left(\frac{x^2}{C_x{}^2} + \frac{y^2}{C_y{}^2} + \frac{z^2}{C_z{}^2}\right)\right]$$

where x,y and z are measured from an origin moving with the cloud at constant speed u, Q is source strength, C_x, C_y, and C_z are virtual diffusion coefficients, and n is a parameter that varies with turbulence and is obtained by fitting the theoretical profile $u = u_0 z^{n(2-n)}$ to the observed variation of wind with height. Maximum concentration is found at the puff's center, where $x = y = z = 0$, so that the expression for the maximum concentration is

$$\chi = \frac{2Q}{\pi^{3/2}C_xC_yC_z(ut)^{3/2(2-n)}}$$

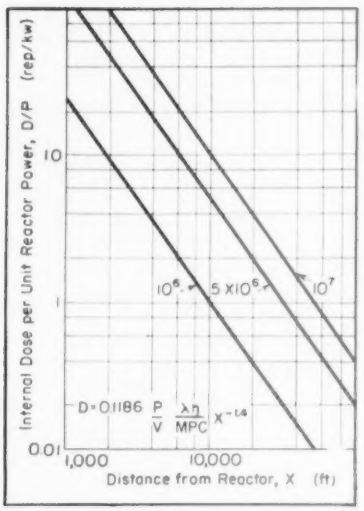

FIG. 3. Maximum *inhalation* dose to the most sensitive organ under *inversion* conditions; $V = 3$ mi/hr. Values on curves are $(\lambda\eta/MPC)$

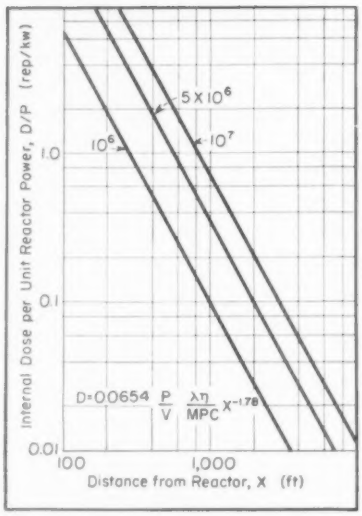

FIG. 4. Maximum *inhalation* dose to the most sensitive organ under *lapse* conditions; $V = 3$ mi/hr. Values on curves are $(\lambda\eta/MPC)$

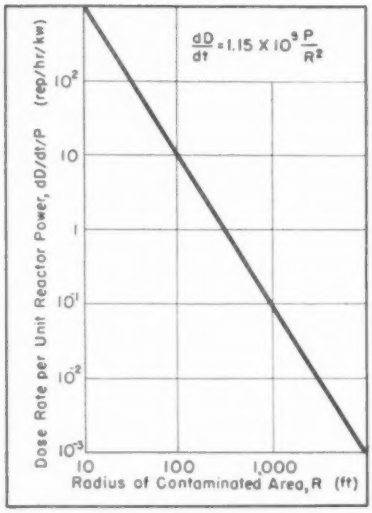

FIG. 5. Initial external-dose rate at the center of a uniformly-covered circular area

For a continuous point source the equation is

$$\chi(x,y,z) = \frac{2Q}{\pi C_y C_z u x^{2-n}} \times \exp\left[-x^{n-2}\left(\frac{y^2}{C_y^2} + \frac{z^2}{C_z^2}\right)\right]$$

At a given distance x downwind, maximum concentration occurs at $y = z = 0$, and is given by

$$\chi = \frac{2Q}{\pi C_y C_z u x^{2-n}}$$

To evaluate hazards from release of radioactive contaminants from a reactor, three cases involving exposure of an observer on the ground should be considered: 1, external γ and β dose; 2, inhalation dose; 3, γ and β dose due to a rainout or fallout.

2. External Doses

Maximum integrated β and γ external doses to personnel directly in the path of the radioactive cloud are given by Fig. 1 for inversion* conditions and by Fig. 2 for lapse† conditions.

The equations on which these curves are based take into account the leakage of gamma radiation from clouds that have small diameters with respect to the mean free path of gamma photons in air. Thus, for low-power research reactors, they seem more realistic‡ for estimating the external gamma and beta hazard than the formula $R = 0.01\sqrt{kw}$, which has sometimes been applied to predict dosages of more than 300 rep (*2, 3*).

To obtain the curves in Figs. 1 and 2, it was assumed conservatively that: 1, radioactivity in the reactor is the maximum to be expected for the assumed power level; 2, cloud is released at ground level as a point source; 3, activity has decayed for 1 minute according to the formula of Wigner and Way (*4*); 4, radioactivity is contained uniformly in a hemispherical cloud whose base is a few feet from the ground; 5, radioactive-contaminant concentration in cloud is maximum predicted by Sutton's formula for a particular distance from source; 6, cloud remains the same size and shape during its approach and departure from observer; 7, beta dose is negligible compared to the gamma dose; 8, gamma absorption by air is negligible; 9, gamma-photon energy is 0.7 Mev; 10, observer remains on the diameter of the cloud's base until all radioactivity has passed.

Diffusion parameters used in plotting all curves are given in Table 1; these represent local conditions.

Inherent Safety

How rapidly power level can rise without damaging a "swimming-pool" type reactor is indicated by extrapolations from extensive boiling tests run by Argonne National Laboratory in the summer and fall of 1953 at the National Reactor Testing Station near Arco, Idaho.

Such extrapolations show that an instantaneous reactivity of 3.8% is self-limiting without serious damage to the reactor if the moderator-coolant is at the boiling point at the start of the excursion. An instantaneous k_{excess} of 1.9% produces similar effects if the water is at ambient room temperature at the excursion's start.

A 3.8% instantaneous k_{excess} is equivalent to suddenly inserting about 3 fuel elements into the lattice. On this type of reactor this means that power level rises by a factor of "e" every 0.0024 sec. Excess reactivity of 1.9% causes power to rise by factor "e" every 0.0065 sec.

* Inversion is the abnormal condition wherein there is an increase in temperature with altitude. Temperature inversions are generally associated with air movements of a nonturbulent variety. Under these conditions, dispersal of airborne contaminants is particularly slow, and these contaminants can be carried far from the point of origin in fairly concentrated form.

† Lapse is the normal atmospheric condition in which temperature and pressure decrease with altitude.

‡ The downwind distance at which the dose falls below 300 rep with a 3 mi/hr-wind and a reactor power of 1,000 kw is seen (in Figs. 1 and 2) to be 520 ft under inversion conditions and 120 ft under lapse conditions. The $R = 0.01\sqrt{kw}$ formula indicates a 1,670-ft distance under inversion conditions.

In general, the average whole-body dose from beta radiation that the downwind observer receives is less than 1% of the gamma dose because the range of beta particles in air is only about 5 ft. However, surface dosages to exposed areas can be quite high.

3. Inhalation Doses

Calculation of inhalation dose an observer might receive if a cloud of radioactive contamination were to engulf him is more complex. In addition to estimating the concentration of contaminants in air inhaled by the observer, account must be taken of the biological half-life (elimination plus decay) of the various isotopes, the particular organs in which the isotopes accumulate, and the sensitivity of these organs to radiation damage. Sutton's equation is used to calculate dose in terms of activity-time per unit volume. Through use of MPC values, this dose is converted to reps delivered to particular body organs (*5*).

Maximum integrated inhalation doses under inversion and lapse conditions are given in Figs. 3 and 4 as functions of distance from the source and the reactor power level; where λ is the fission yield of a particular isotope, η is fraction of equilibrium reached in reactor at time of incident, *MPC* is maximum permissible concentration of the particular isotope in the body.

The curves in Figs. 3 and 4 were calculated assuming that: 1, reactor has operated continuously at constant power of 1 Mw; 2, equilibrium fraction was calculated at 10% burnup; 3, isotope fission yield is the yield of the particular mass number; 4, fission products are released at ground level as a point source; 5, concentrations downwind are given by Sutton's diffusion formula; 6, observer remains directly downwind while all activity passes; 7, retention of any particular isotope equals that assumed in ref. (*4*) for calculating maximum permissible concentrations.

Table 2 gives dose parameters for use in determining internal doses from Figs. 3 and 4. The particular organs affected are also listed.

4. Doses from Fallout

Rain or other climatic conditions that would accelerate fallout of radioactivity shortly after the contaminated cloud forms could create dangerously radioactive areas near the reactor site.

If radioactivity falls out, the resulting dose rate is primarily a function of the source strength per unit area.

The fallout beta dose rate to a fully-clothed observer has been neglected. Figure 5 shows the gamma dose rate as a function of the contaminated radius and the reactor power for fallout of all the fission products uniformly over a circular area. To properly estimate the size of the contaminated area and its activity, Fig. 6 together with information on the rate of fallout and wind velocity should be used. A rainout rate of 1%/min has been suggested as a conservative assumption (*6*). Figure 6 estimates, from Sutton's formula, the equivalent cloud radius or the width of a cloud of contaminants that originate as a point source.

5. Reducing Hazards

Several steps can be taken to reduce these hazards. The most important step involves designing the reactor so that any nuclear incident is inherently self-limiting before the reactor generates enough energy to volatilize the fuel and fission products. Water-moderated homogeneous reactors are particularly good examples of this type of design. The "swimming pool" reactor type (*7*) to be constructed at the University of Michigan is another type that shows remarkable self-limiting properties.

A building or other enclosure designed to contain the products of a nuclear incident can be constructed. This has been done for the submarine reactor (SIR-1) being constructed at West Milton, New York. The reactor building at the University of Michigan is being designed so that escape of contaminants from inside the building can be limited to less than 10% per 24 hr. This reduces the potential hazard by orders of magnitude.

* * *

Calculation details are shown in ref. (8). The help of William K. Luckow and E. Wendell Hewson in the preparation of the material used in this article is greatly appreciated.

TABLE 1—Diffusion Parameters

Vertical temperature gradient	u *(m/sec)*	n	C_x $(m^{n/2})$	C_y $(m^{n/2})$	C_z $(m^{n/2})$
Moderate lapse	6	0.22	0.30	0.30	0.25
Large inversion	2	0.60	0.22	0.22	0.12

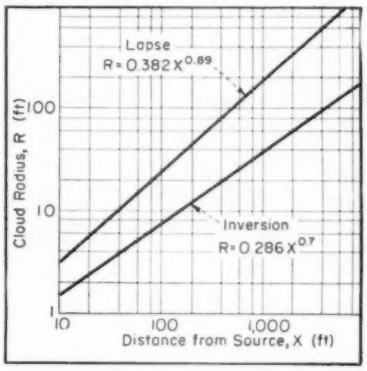

FIG. 6. Equivalent cloud radius

TABLE 2—Dose Parameters, Critical Organs for Various Fission Products

Isotope	$\frac{\lambda\eta}{MPC_i}$ *(ml/μc)*	*Organ*
Rb^{86}	5.0×10^4	muscle
Sr^{89}	2.3×10^6	bone
$Sr^{90} + Y^{90}$	5.9×10^6	bone
Y^{91}	1.7×10^6	bone
Nb^{95}	1.6×10^5	bone
Mo^{99}	3.0×10^3	bone
Tc^{96}	2.1×10^4	kidneys
$Ru^{106} + Rh^{106}$	7.4×10^4	kidneys
Rh^{105}	9.0×10^3	kidneys
$Pd^{103} + Rh^{103}$	5.3×10^4	kidneys
Ag^{105}	5.0×10^2	liver
Te^{127}	2.0×10^4	kidneys
Te^{129}	2.5×10^5	kidneys
I^{131}	9.7×10^6	thyroid
$Cs^{137} + Ba^{137}$	5.2×10^3	muscle
$Ba^{140} + La^{140}$	1.0×10^6	bone
La^{140}	6.0×10^4	bone
$Ce^{144} + Pr^{144}$	4.0×10^6	bone
Pr^{143}	7.3×10^4	bone
Pm^{147}	1.1×10^4	bone
Sm^{151}	8.6×10^2	bone
Eu^{154}	1.4×10^3	bone

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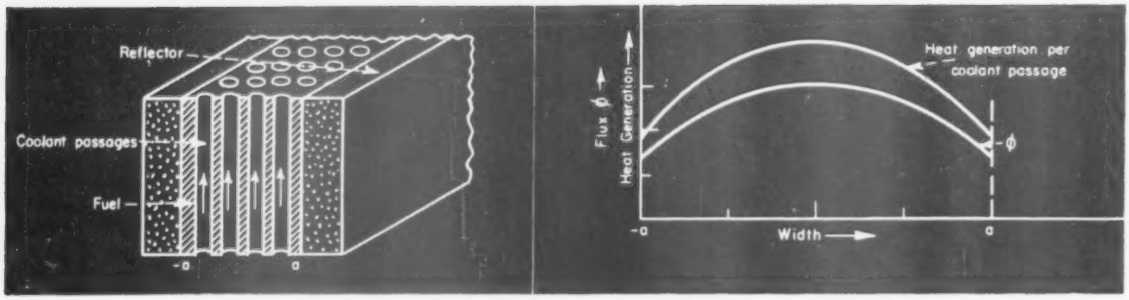

FIG. 1. Distribution of neutron flux and heat generation for uniform coolant distribution in an infinite slab reactor

Nonuniform Fuel Distributions in Nuclear Reactors

Substantial advantages can be gained from nonconventional distribution of reactor fuel, coolant, or moderator. Redistribution of coolant can increase heat-removal potential of fast reactors by 20%. Higher power output can be gained from thermal reactors by using nonuniform fuel positioning

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REACTOR DESIGNS, for the most part, use a uniform distribution of materials throughout the reactor core. Such designs are usually the easiest to calculate and are often the simplest to construct as well. But many advantages can be gained from utilization of a nonuniform material distribution. This article emphasizes the possibilities inherent in designs of this type and illustrates these possibilities by specific examples.

In most reactor designs there are, of course, nonuniformities in distribution of materials. Examples of such nonuniformities include use of different materials in one region of a reactor than in another, and nonuniform material distribution on a "microscopic" scale. The former case is illustrated by a fast reactor in which a blanket made up largely of natural or depleted uranium surrounds a core containing a rather high concentration of fissionable material. The latter case is exemplified by a Hanford reactor, in which the uranium is lumped into a lattice structure. The "microscopic" sort of nonuniformity is, of course, present in all reactors in which fuel, moderator, coolant, or structural elements of finite dimensions are employed.

Marked advantages can also be gained from variations on a macroscopic scale within a single region of a reactor. Some of these advantages are higher power output, smaller critical mass, higher average coolant outlet temperature, longer periods between refueling, higher breeding gain, and higher burnup of fissionable material. These advantages may not all be realized in any one distribution. Selection of the proper distribution will be fixed by technical and economic requirements of the reactor under consideration.

Three illustrative examples of reactors with nonuniform material distributions will be considered:

1. A single-energy ("fast") reactor with uniform power generation per coolant passage.

2. A thermal reactor with uniform power generation per unit mass of fuel (and, incidentally, minimum critical mass).

3. A thermal reactor having uniform power generation per unit volume of core.

Fast Reactor

In a reactor, neutron flux generally varies with position. Heat generation per unit volume is proportional to the product of the macroscopic fission cross section and the flux. Thus, uniform distribution of fuel results in nonuniform volumetric heat generation. Coolant flowing through the regions of lower heat-generation intensity removes less heat than coolant passing through the region of high-intensity heat release. The resultant

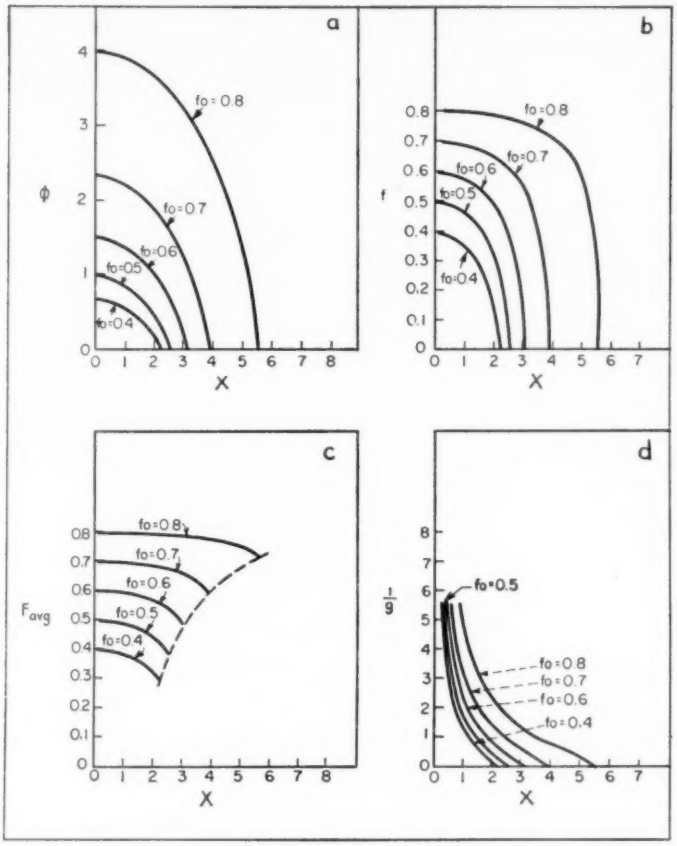

FIG. 2. Solution for uniform heat generation per volume of coolant in a single-energy fast reactor. Reactor infinite flat plate, coolant treated as void

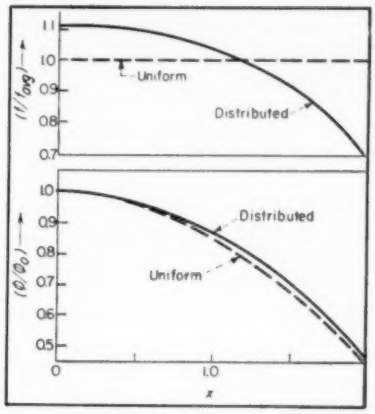

FIG. 3. Distributed cooling in flat-plate fast reactors. f_{avg} is 0.45; half-thickness, 2λ

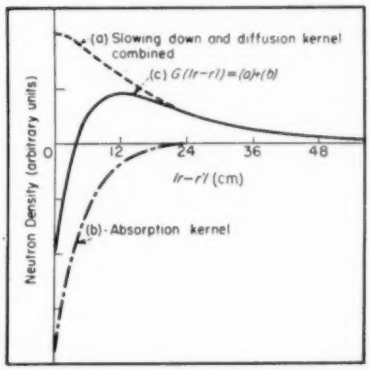

FIG. 4. Construction of a typical volcano kernel for a thermal reactor

coolant temperature rise is, therefore, not uniform throughout the reactor. In effect, only a few coolant passages are being worked to their maximum capacity.

Figure 1 shows the situation for a flat-plate reactor surrounded by a nonmultiplying reflector. In this case, it is usual for the coolant flow to be axial. With a uniform distribution of the coolant, the temperature rise across the central coolant passage is higher than that across any of the other coolant passages. To obtain a uniform coolant temperature rise, the heat generation per unit volume should be proportional to the percentage of the volume occupeid by the coolant.

This analysis considers a redistribution of the coolant passages in a plane normal to the direction of flow. It is assumed that the composition of the fuel material itself remains unchanged, with the redistribution being effected by exchanging fuel for coolant and vice versa. It is also assumed that the reactor can be described adequately by a monoenergetic neutron picture.

One would expect, intuitively, that the desired result could be achieved by increasing the volume of coolant near the center of the core while decreasing the volume near the edge. Since this results in moving fuel toward the edge of the core, it would also be expected that the reactor critical mass might increase. Actual analysis shows that these expectations are both realized,* but that the redistribution in most cases is small enough to result in only a minor increase of critical mass.

In analyzing this case, the following conditions are assumed to prevail:

1. One energy group.
2. Diffusion theory.
3. Geometry: core an infinitely long and wide flat plate surrounded by a nonmultiplying reflector.

* In the example of an infinite slab reactor, critical mass is unchanged. In more realistic finite slab or cylindrical configurations, the mass does increase.

4. Uniform composition of fuel material (variations in over-all core composition to be made by substituting coolant for fuel material or vice versa).
5. Negligible coolant scattering and absorption cross sections.

The following equation, based on diffusion theory, must be solved

$$\frac{d}{dr}\left(D\frac{d\phi}{dr}\right) + (k-1)\Sigma_a\phi = 0 \quad (1)$$

Equation 1 is subject to the usual boundary conditions of symmetry at the core centerline and continuity of both neutron flux and neutron current at the core-reflector boundary. For simple one-dimensional cases, the latter two conditions can be lumped into a single boundary condition requiring continuity of the product of the diffusion constant and the first derivative of the logarithm of the flux. At the boundary, then

$$-D\frac{d}{dr}\log\phi = Y \quad (2)$$

SYMBOLS

$f(r)$ = volume fraction of coolant
$D(r) = D_1/(1-f)$ = diffusion coefficient
$\Sigma_a(r) = \Sigma_{a1}/(1-f)$ = absorption cross-sections
D_1, Σ_{a1} = constants
ϕ = neutron flux (in thermal reactors, thermal neutron flux)
K_1, K_2, K_3 = constants of proportionality
r, r' = distance from reactor plane of symmetry
k = multiplication constant of fuel
$\lambda = \sqrt{D_1/[(k-1)\Sigma_{a1}]}$
$x = r/\lambda$
$f_0 = f(0)$
$y = \int (1-f)dx$ = parameter used in solution of Eq. 1
$f_{avg} = \int_{core} f\,dx \Big/ \int_{core} dx$
$1/g = -\phi/(d\phi/dy)$
$Y = (-D/\phi)d\phi/dr$ = reflector admittance at the core-reflector interface
$\rho(r)$ = fuel density
$\varkappa$ = fuel absorption cross-section per unit mass
$G_0(|r-r'|)/\eta$ = thermal flux at r' in pure moderator arising from one fission neutron born at r
η = number of fission neutrons born per neutron absorbed in fuel
$-G_1(|r-r'|)$ = the thermal flux at r' in pure moderator arising from one thermal neutron born at r
$G = G_0 + G_1$ = volcano kernel

where Y is a characteristic parameter of the given reflector. From condition 5, one obtains, with constant D_1 and Σ_{a1}

$$D = \frac{D_1}{(1-f)} \tag{3}$$

$$\Sigma_a = \Sigma_{a1}(1-f) \tag{4}$$

It is required that the power per unit volume be proportional to the coolant volume, so that

$$(1-f)\,\phi = K_1 f \tag{5}$$

Let

$$\lambda = \sqrt{\frac{D_1}{(k-1)\Sigma_{a1}}} \tag{6}$$

From Eqs. 1-6, one obtains

$$f = \frac{f_0 \cos y}{1 - f_0 + f_0 \cos y} \tag{7}$$

$$f_{avg} = \frac{f_0 \sin y}{(1-f_0)y + f_0 \sin y} \tag{8}$$

$$x \equiv r/\lambda = \left[y + \frac{f_0}{1-f_0} \sin y \right] \tag{9}$$

$$\phi = K_2 \cos y \tag{10}$$

$$g = \tan y \tag{11}$$

At the boundary

$$\frac{1}{g} = \frac{D_1}{(\lambda Y)} \tag{12}$$

Figure 2 gives these results in graphical form, with ϕ, f, f_{avg}, and $1/g$ plotted against x for various values of the parameter, f_0. In use, one generally knows Y from the reflector properties. Choosing f_0, the critical outer core dimension can be found from Eq. 12 and Fig. 2*d*. Figures 2*a*, *b*, and *c* then give the flux distribution, the coolant distribution, and the average coolant fraction.

It can be seen from Fig. 2*b* that, for a bare reactor, the requisite range of the coolant fraction is quite large. This range decreases rapidly with increase in reflector thickness, so that structurally practicable variations in coolant fraction are available with reasonable reflector thicknesses. It is likely that, in practice, the coolant distribution would be approximated by a number of regions, each of uniform coolant distribution.

A comparison of a reactor having uniform coolant distribution with a reactor having distributed coolant is given in Fig. 3. Flux is changed only slightly by the redistribution of coolant. However, the heat removal capability for a specified maximum coolant temperature rise is increased 20%. The unchanged outer dimension of the core is a peculiarity of the slab geometry employed in this simplified analysis. In the more realistic cylindrical and spherical geometries, a small increase in core size results from the redistribution.

Solutions to the problem discussed in preceding paragraphs have been obtained not only for the slab geometry but also for spherical and cylindrical geometries, both with coolant treated as void and with coolant treated as nonabsorbing scatterer. These results, while fairly complicated to obtain, yield curves similar to those in Fig. 2. With the aid of the curves, such cases are easily studied.

Thermal Reactors

The probability of leakage divided by the probability of capture in fuel increases with neutron speed. If the neutrons are slowed to low speeds, much less uranium is needed to catch the neutrons before they leak. Slowing down of the neutrons can be accomplished by introducing a light element known as a moderator. Hydrogen, deuterium, beryllium, and carbon are the elements most commonly used for this purpose. If sufficient moderator is present, the neutrons will be slowed down until they are in thermal equilibrium with the moderator atoms. Such equilibrium neutrons are known as "thermal neutrons."

Volcano Kernel

Consider (for simplicity) an infinite, uniform moderator into which fuel is so dispersed as to constitute a critical thermal reactor. The region of the reactor that contains the fuel is the core.

Let $\rho(r)$ be the fuel density at r. The number of neutrons absorbed by fuel at r can be written as $\varkappa\rho(r)\phi(r)$, where $\varkappa$ is a constant characteristic of the fuel, moderator, and temperature, but independent of r. Capture of neutrons in the fuel gives rise to fissions and new neutrons. Before these new neutrons, born in fission, can produce further fissions, they must be slowed down to thermal energy. During the slowing-down process, the neutrons diffuse from the point r where they were born. The neutrons diffuse farther while they are thermal. Thus, a neutron absorbed in the fuel at r produces thermal neutrons and thus further fissions at r'. Curve *a* of Fig. 4 shows the flux of thermal neutrons that arises at r' because of the fission neutrons produced from one neutron absorbed by fuel at r, as it would occur in a pure moderator.

To take into account the presence of the fuel, the effect on the thermal neutron flux that arises from the absorption of a thermal neutron by a fuel atom at r must be added to curve *a* of Fig. 4. The depression of thermal neutron flux at r' caused by the absorption of a thermal neutron at r is clearly equal to the increase in thermal flux at r' caused by the birth of a thermal neutron at r. In this manner one obtains curve *b* of Fig. 4, which gives the depression of thermal neutron flux at r'

that is due to a thermal neutron absorbed at r; curve b, which represents the absorption kernel, is the negative of the diffusion kernel.

The sum of the two effects yields the net effect on the thermal neutron flux caused by absorption of a thermal neutron in fuel. This resultant, plotted as curve c in Fig. 4, is called a volcano kernel. The equation of this curve will be written as $G(|r - r'|)$. The volcano kernel is characteristic of the moderator and of the fuel composition, but is independent of the fuel distribution, $\rho(r)$.

If the number of neutrons absorbed in fuel per unit volume is known, one can immediately use G to calculate the thermal neutron flux. Thus, remembering that $\varkappa\rho\phi$ is the number of neutrons absorbed in fuel per unit volume, one has as the equation relating the absorption of thermal neutrons in fuel to the thermal flux

$$\phi(r') = \int_{core} \varkappa\rho(r)\phi(r)\, G(|r - r'|)\, dr \tag{13}$$

Equation 13, which is satisfied by a critical reactor, will be the basis for the following discussion.

Uniform Power per Unit Mass

For uniform power per unit mass of fuel, the power (and thus the fission density) must be proportional to the fuel density, ρ. Since the power is proportional to $\rho\phi$, ϕ must be constant in the core. This analysis yields the equation that ρ must satisfy

$$\phi = \varkappa\phi \int_{core} \rho(r)\, G(|r - r'|)\, dr$$

or

$$1 = \varkappa \int_{core} \rho(r)\, G(|r - r'|)\, dr \tag{14}$$

Equation 14 must hold for all points r' in the reactor core; it is solved for $\rho(r)$ to determine the required fuel distribution.

Solution of Eq. 14 shows that there is a maximum size core for which the thermal flux can be maintained constant for a given moderator and fuel. Such a solution is given as curve a of Fig. 5. In seeking a solution for a smaller core region, one finds such a solution with a fuel distribution in which part of the fuel is concentrated at the core-reflector interface, and the remainder is distributed over the core. Such a fuel distribution is shown as curve b of Fig. 5. The lumped fuel is indicated by a bar having an area proportional to the fuel concentrated at the core-reflector interface.

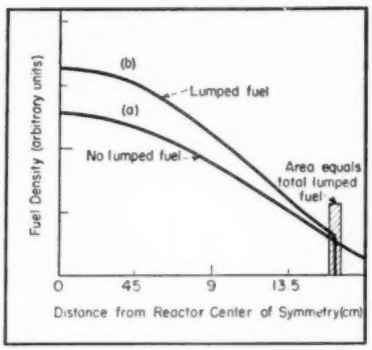

FIG. 5. Fuel distributions giving uniform power per unit mass of fuel in a thermal reactor

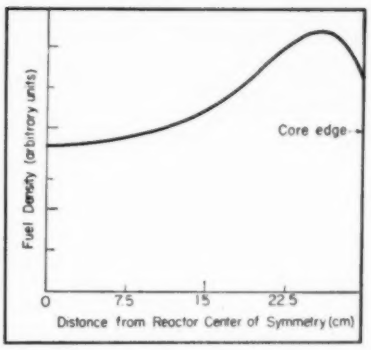

FIG. 6. Fuel distribution giving uniform power per unit volume of core in a thermal reactor

Considering all reactors that can be constructed by distributing a given fuel in a given infinite, uniform moderator, it is interesting to note that curve a of Fig. 5 offers a fuel distribution that yields the reactor with minimum critical mass. In some cases, a core of smaller dimension than the minimum critical mass reactor may be required. In such a case, the fuel distribution of curve b of Fig. 5 will result in the smallest critical mass for the core dimension. Such a critical mass will, however, be larger than that of curve a.

Uniform Power per Unit Volume

The power per unit volume of core is given by $\rho\phi$. Thus, the condition of uniform power generation per unit volume of core may be written as $\rho\phi = K_3$. By combining this relationship with Eq. 13, one immediately obtains the expression

$$\phi(r') = \varkappa K_3 \int_{core} G(|r - r'|)\, dr$$

whence, for points r' in the core

$$\rho(r') = \frac{K_3}{\phi(r')} = \frac{1}{\varkappa \int_{core} G(|r - r'|)\, dr} \tag{15}$$

A typical fuel distribution, as calculated from Eq. 15 for the volcano kernel of Fig. 4, is plotted in Fig. 6.

Whereas these cases, for simplicity, have been discussed as if there were an infinite, uniform moderator into which the fuel was to be inserted, the treatment of practical cases leads to similar results, but with a great deal more effort in calculation or experiment. The major feature emphasized by considering finite moderating regions is that there must be an unfueled region (reflector) surrounding the core to obtain uniform power, either per unit fuel mass or per unit core volume.

Conclusion

Several advantages that one might hope to obtain by nonuniform distribution of materials in a reactor have been listed. Not all of these advantages can be attained at the same time, however. A particular case, the advantage of obtaining higher power output, has been considered for three different reactor design criteria and appears to outweigh the possible increase in construction difficulty for several applications. These results are, nevertheless, only a first attempt to solve the problem of utilizing nonuniform distributions. It is to be expected that continuing experience and effort will show that additional advantages can be obtained by tailoring a reactor's characteristics to the job for which it is intended.

* * *

This article is based on a paper presented at the American Institute of Chemical Engineers' International Congress on Nuclear Engineering, Ann Arbor, Michigan, June 22, 1954. The considerations with regard to fast reactors were developed in conjunction with work performed on the nuclear power development project of Dow Chemical-Detroit Edison and Associates. The considerations on thermal reactors were developed in conjunction with a subcontract from Oak Ridge National Laboratory and from Pratt and Whitney Aircraft. Thanks are due to our many colleagues at Nuclear Development Associates, Inc., especially to J. E. Wilkins, Jr., under whose supervision the various curves used in the fast reactor study were determined. Furthermore, the use of the volcano kernel in obtaining the fuel distribution for a reactor with uniform power per unit core volume was suggested by Dr. Wilkins.

GLASGOW CONFERENCE

International Developments in Nuclear Physics

New techniques for determining the half-life of short-lived isomeric transitions, experiments on photodisintegration and Coulomb excitation, new results in meson theory, beta decay and nuclear structure, are discussed in this article that summarizes the progress in nuclear physics to July, 1954

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THE BROAD PLAN of the Glasgow conference was to survey the present knowledge of nuclear and meson physics, and to focus specialists' attention on problems outside their own particular field. To this end each main session began with one or more survey papers, followed by shorter ones.

In an article of this size it is clearly impossible to report on each of the 105 papers presented; therefore only those parts of the conference that the author personally found most stimulating will be discussed. For a full report, the reader is referred to the conference proceedings.*

Nuclear Fluorescence

F. R. Metzger (Bartol Research Foundation) and **K. Ilakovac** (Birmingham) independently described experiments on the fluorescent scattering of γ-rays. As nuclear level widths are so small, it is necessary to use source and resonant nuclei of the same nuclide in order that the incident γ-ray energy should be exactly equal to the energy level difference in the resonant nucleus.

Even if this is done, however, fluorescence does not automatically occur, for the nucleus recoiling after γ-emission will take some energy with it. It is therefore necessary to give this energy back to the γ-ray if fluorescence is to take place, and Metzger described two ways by which this can be done.

The first is by giving the nuclei a velocity by mechanical means, and letting the Doppler effect supply the required energy—a method also used by Moon and his co-workers (*1*). The second method uses the thermal agitation of the source or resonating nuclei to give extra velocity to the nuclei.

Using the first of these methods a value of $(9 \pm 4) \times 10^{-10}$ sec was obtained for the half-life of the 280-kev level in Tl^{203}. Using the second method, the half-life of the 411-kev level in Hg^{198} was found to be $(3.3 \pm 0.3) \times 10^{-11}$ sec. Other values obtained by this second method were for the 209-kev gamma level in Hg^{199}, $3 \pm 1 \times 10^{-10}$ sec.; for the 280-kev level in Tl^{203}, $10 \pm 4 \times 10^{-10}$ sec, in agreement with the result obtained by the first method.

Ilakovac used the fact that Cu^{63} nuclei produced by β-decay of Zn^{63} would have additional velocity due to the positron and neutrino recoil, and that therefore the γ-rays emitted by Cu^{63} would have a spread of energy. For the recoils in the right direction, the Doppler shift could compensate for the loss of energy due to the recoil of the Cu^{63} nucleus after γ-emission, and therefore some fluorescent scattering could be expected. This he found, and estimated the half-life of the 0.96 Mev level in Cu^{63} to be 6×10^{-13} sec.

Coulomb Excitation

G. M. Temmer and **N. P. Heydenburg** (Department of Terrestrial Magnetism, Carnegie Institute, Washington, D. C.) reported experimental work on Coulomb excitation of nuclear levels (*2*).

In this process the nucleus is excited by an incident charged particle that does not penetrate into the nucleus. Rather the excitation of the nucleus is due to the long-range Coulomb field of the incident particle.

Alpha particles accelerated by an electrostatic generator were used as bombarding particles. They more readily satisfy the criterion for non-penetration of the nucleus: that the classical distance of closest approach be large compared to the deBroglie wavelength of the incident particle, $2Z_1Z_2e^2/\hbar v \gg 1$. It also turns out that alpha particles are relatively much less effective than protons in exciting the characteristic K-shell X-rays of the target element, thus lessening the undesired background.

Temmer and Heydenburg's research

* Proceedings will be published shortly by The Pergamon Press, Ltd., 242 Marylebone Road, London, N. W. 1.

has been carried out mainly with rare-earth elements far from magic numbers, whose nuclei may therefore be expected to be more deformable than those of other nuclei not so situated in the periodic table. The results are in agreement with some of the predictions of the Bohr-Mottelson collective model of the nucleus (*3*), and cast new light on the location and nature of low-lying energy levels.

Interaction in β-decay

C. S. Wu (Columbia) gave an account of the present ideas on the nucleon interaction that takes place during β-decay.

Two important experiments were discussed. The first of these, performed by B. M. Rustad and S. L. Ruby (*4*) determined the angular correlation between the recoil nucleus and the beta particle in the decay of He^6.

The second experiment, performed by J. S. Allen and W. K. Jentschke (*5*), determined the electron-neutrino angular correlation by measuring the energy spectrum of the recoil Li^6 nucleus by a time of flight method.

The results of these experiments give conclusive evidence in favor of tensor interaction under Gamow-Teller selection rules.

Similar experiments, Dr. Wu thought, should be carried out on $0^+ \rightarrow 0^+$ β-transitions to choose between scalar and vector interactions under Fermi selection rules. As molecular gases are not suitable as β-ray sources for this type of work, she hoped that ample supplies of A^{31} could soon be produced.

Dr. Wu further described the work that had gone into the theory of pseudoscalar interaction as a result of the attempts to explain the RaE β-spectrum. So far as this particular nucleus is concerned, the work has turned out to be unnecessary, for Dr. Wu reported a pre-publication result of K. Smith (Cambridge, England): the ground state of RaE has spin 1 and not 0 as previously thought.

Photodisintegration

New methods of investigating photodisintegration were described by **H. W. Koch** (NBS, Washington, D. C.). Nuclear absorption measurements have been carried out by passing the X-ray beam from a 50-Mev betatron through long absorbers. Elastic scattering experiments have also been conducted. In both cases the X-ray detector was a cylinder of NaI, 5 in. in diameter and 9 in. long.

Absorption bands have been found in the transmission spectrum due to the giant resonance absorption, and there is some evidence for single-level absorption as well. In the scattering work, cross-section curves in general show two peaks, one at an energy corresponding to the giant resonance, and another at about the threshold energy.

U. Fano (NBS) suggested that the reason for this behavior might be found if scattering experiments were regarded as ones in which one measured the "polarizability" of the nuclear material, as in the analogous case of optical scattering. If this polarizability is α, the σ_{abs} is given by the imaginary part of α, and σ_{elast} by $|\alpha|^2$, a summation being taken over all available levels. In a region of discrete levels or absorption bands the average of $|\alpha|^2$ will be large compared with the average of α, but if there are no discrete levels, then $(|\alpha|^2)_{avg}$ will show a similar shape to the average of α.

This evidence for discrete energy levels in the photodisintegration process was supported by results reported by **J. R. Atkinson** (Glasgow). The Glasgow cloud chamber group have found distinct proton groups produced during the photodisintegration of N^{14}.

D. H. Wilkinson (Cambridge, England) outlined a possible theory to explain the photodisintegration process in terms of the shell model. This had been reported previously at Philadelphia in May. Among other results, the theory gives the half-width of the giant resonances near closed shells as much narrower than those of nuclei far from closed shells, for in these latter cases nuclear interaction will broaden the resonance. This agrees with experiment.

The integrated cross sections Wilkinson obtains are in fair agreement with experimental data. However, the theory did not appear to meet with unanimous support from the theorists present.

Nuclear Models

A session on nuclear data and nuclear models was opened by **J. A. Wheeler** (Princeton). He spoke particularly of the work of K. A. Brueckner at the

Conference Background

Between July 12th and 17th, this International Conference on Nuclear Physics was held in Glasgow University, Scotland, under the general chairmanship of Professors P. I. Dee and J. C. Gunn. The meeting was sponsored by the International Union of Pure and Applied Physics and UNESCO; 336 delegates from 24 countries were present.

Glaser Bubble Chambers—A New Research Tool

Bubble chambers produce tracks when an ionizing particle passes through a superheated liquid, much as cloud chambers do using supersaturated vapors. One very striking advantage of bubble chambers over cloud chambers is the greater density of the liquid medium, which means a greater likelihood both for an event to occur in the chamber and for the full range of secondary particles to lie within the chamber. The first investigations were by Donald A. Glaser of the University of Michigan who studied the effects of ionizing radiation on the formation of bubbles and the boiling of liquids (9).

At the Glasgow conference R. H. Hildebrand (Chicago) described the theory and practice of these bubble chambers. He showed photographs of tracks in a liquid pentane chamber which were remarkable for the lack of background tracks. Although this was partly due to very good beam collimation; rapid expansion and good photography also played an important part in the clarity of the pictures.

Further work is being carried out with liquid hydrogen chambers; the Chicago bubble chambers are still small, but chambers ¼ in. in diameter and 3 in. deep are being made at Berkeley (10).

PI MESONS:

New Significance for Isotopic Spin

Isotopic spin, T, is a quantum mechanical quantity designed to reflect the charge state of particles. Isotopic spins combine after the fashion of ordinary angular momenta and spins, and must be considered in applying the Pauli principle. The original application was to nucleons, for which $T = {}^1/_2$, $T_z = {}^1/_2$ *corresponding to the proton, while* $T_z = -{}^1/_2$ *represented the neutron.*

Recently the description of charge state in terms of isotopic spin has been extended to π *mesons for which* $T = 1$, *and* $T_z = \pm 1, 0$ *corresponds to the* $\pm$ *and* 0 *charge states of the pion. The validity of the implicit assumption of charge-independence for mesons will be tested by the comparison of theoretical prediction and experiment in pion-nucleon interactions of the type considered here.*

University of Indiana. In an attempt to derive an effective nuclear potential, Brueckner considers an infinite nuclear medium with a test nucleon passing through it. As in the optical case, a refractive index can be derived that represents the scattering of the nucleon, the refractive index representing a relation between wavelength and frequency, or, more usefully, momentum and energy. In this theory the scattered nucleon has a mass inside the nucleus different from that of a free particle, a concept that makes it easier to reconcile Brueckner's ideas of a freely moving particle with the current views of the strength of the interaction between nucleons.

So far, Brueckner's treatment has not dealt with the behavior of nucleons near the nuclear surface. The interaction with the nuclear wall can give rise to collective modes of oscillation, analogous to those that take place in molecules. In fact there exists experimental evidence for this analogy: the fission cross section of thorium exhibits a resonance peak at a certain neutron energy similar to peaks that occur in the fission of the oxygen molecule by electrons.

This connection with molecular physics was taken up by **V. F. Weisskopf** (MIT) who felt that nuclear physicists would have to learn from the solid-state physicists, particularly those who dealt with such problems as liquid He II and superconductivity. This importance of the many-body problem had previously been stressed by **H. S. W. Massey** (University College, London).

With regard to Brueckner's theory of the nucleus, Weisskopf felt it was a step in the right direction, in so far as Brueckner was trying to explain internal nuclear forces by the same forces as those encountered in free nucleon interaction, but he thought that one should go farther along the same road, and regard the mass of the nucleon as being the same inside or out.

Mass-19 nuclei. Two self-consistent theory and experiment papers were presented by **D. H. Wilkinson** (Cambridge, England) and **B. H. Flowers,** (Harwell). Flowers started on the basis that the O^{16} nucleus, being doubly magic, would act as a solid core as far as two or three nucleons outside it were concerned and that all low-lying levels of even parity of the nuclei of mass $16 + n$, with $n = 2$ or 3, arise from configurations of the type $\sum_x d^{n-x}s^x$ where x is the number of nucleons raised from the d state to the s state. On this basis, using reasonable parameters, Flowers has been able to calculate low-lying even-parity energy levels for O^{18}, O^{19} and F^{19}.

Wilkinson reported work at Cambridge on F^{19}, and his results agree very well indeed with the calculated values of Flowers in energy and spin. Also in agreement with experiment are the magnetic moment of F^{19}, the ft values for Ne^{19} and O^{19}, and the mass differences between F^{19} and O^{19}, F^{19} and Ne^{19}, and F^{17} and O^{17}. For lack of data, the O^{18} levels cannot be compared with experiment.

Scattering Experiments

Work on p-p scattering done at Harvard and Brookhaven was discussed by **N. F. Ramsey** (Harvard). At Harvard the differential cross section at 90 deg in the center-of-mass system has been measured as a function of proton energy from 38 to 95 Mev (laboratory energy). The experimental points connect smoothly onto the previous results for 32 and 120 Mev obtained at Berkeley.

Chen and Shapiro at Brookhaven have measured the total p-p scattering cross section between 400 and 1,300 Mev, and they find that it rises with energy. Plotting all the available p-p cross sections versus energy, it is clear that there is a broad minimum. The breadth of this minimum led previous workers to the conclusion that the cross section was independent of proton energy.

Interesting results with p-d scattering were independently reported by **D. O. Caldwell** (UCLA) and **J. Rotblat** (St. Bartholomew's Hospital, London). Caldwell measured the angular distribution of 20.6-Mev protons scattered by deuterium gas and found that apart from the familiar deep minimum near 130 deg (center-of-mass angle), there was a shallower minimum near 20 deg, which is apparently due to Coulomb-nuclear interference. Rotblat stated that with 9.5-Mev protons a definite peak was obtained at 40 deg in the angular distribution curve, and that the latest results showed a minimum at smaller angles, in agreement with Caldwell's data.

Theory of Nuclear Forces

A successful theory of nuclear forces is not yet with us, but theoretical effort has been stimulated by calculations stemming from the approach of M. M. Lévy (École Normale Superieure). **R. E. Marshak** (Rochester) gave a report on the status of the meson theory of nuclear forces. This report was the result of discussions with Lévy.

Marshak said that the theory of mesons had been greatly helped by parallel progress in quantum electrodynamics and the formulation of the method of renormalization to obtain finite answers. The same techniques can be applied to the meson field, if the mesons are either scalar with scalar coupling or pseudoscalar, PS, with pseudoscalar coupling (PS).* As mesons are pseudoscalar, a renormalizable meson field theory exists if one assumes pseudoscalar coupling of the pion to the nucleon.

The only way of finding if this latter assumption gives valid results is to work out the two-nucleon interaction and check the results with experimental

* A pseudoscalar meson is one of zero spin and negative parity. Pseudoscalar coupling means that in the Hamiltonian for the system the meson field is coupled to the nucleon field through the gradient of the latter.

data. This calculation is a very formidable task, for to give the observed strength of the two-nucleon interaction the PS(PS) coupling constant needs to be so large ($G^2/4\pi \approx 10$–15) that the fourth-order terms have to be taken into account. This labor has been tackled, although incompletely, by the Tamm-Dancoff method, which is an improvement over the usual perturbation approximation method.

Calculations of sixth- and higher-order terms are in an even more rudimentary state, and unfortunately Klein's work (*6*) implies that the higher-order interactions are in fact comparable in magnitude to the second- and fourth-order terms.

Despite these difficulties, attempts have been made to fit the predictions of the second-order static nuclear potential plus crude versions of the fourth-order terms with the low-energy p-p scattering data. A completely satisfactory fit is not achieved with any of the static potentials derived from the PS(PS) theory, although it must be borne in mind that all the calculations are far from being completely satisfactory themselves. At higher energies, higher-order terms become even more important in the theory. One may conclude that no fair attempt has yet been made to compare the PS(PS) theory with experiment.

TABLE 1—Properties of Heavy (K) Mesons

Decay scheme	*Q value (Mev)*	*Mass (in electron masses)*	*Half-life (sec)*	*Certainty**
$\tau^{\pm} \rightarrow \pi^{\pm} + \pi^{+} + \pi^{-}$ $(\tau^{\pm} \rightarrow \pi^{\pm} + \pi^{0} + \pi^{0})$†	75 ± 0.5	966 ± 4	$> 10^{-8}$	A (47 cases)
$\theta^{0} \rightarrow \pi^{\pm} + L^{\mp}$ ‡	214 ± 5	965 ± 10	$1.7^{+0.6}_{-0.3} \times 10^{-10}$	A
$\kappa \rightarrow \mu + 2$ or more neutrals		1,200–1,300 (?)	$\geq 10^{-9}$	B
$K_{\mu}{}^{+} \rightarrow \mu^{+} + \nu$		912 ± 20		B
$\chi \rightarrow \pi + 1$ neutral		950–980		C
$S \rightarrow \mu^{+} + 1$ neutral		1,200		C

* Certainty: A = Certain, B = Probable, C = Likely

† Some evidence exists that this alternative mode occurs in 20 or 30% of cases of τ-meson decay.

‡ The L-meson in this decay is probably a π, but it could be a μ.

TABLE 2—Properties of Hyperons (Y-particles)

Decay scheme	*Q value (Mev)*	*Mass (in electron masses)*	*Half-life (sec)*	*Certainty**
$\Lambda^{0} \rightarrow p + \pi^{-}$	37	2,182 ± 2	$3.7^{+0.5}_{-0.6} \times 10^{-10}$	A
$Y^{-} \rightarrow \Lambda^{0} + \pi^{-}$	65	2,582 ± 10		A
$Y^{\pm} \rightarrow n + L^{\pm}$	114 ± 10	2,330 ± 20	$\sim 3 \times 10^{-10}$	B
$Y^{+} \rightarrow p + \pi^{0}$	116 ± 2	2,326 ± 5	$\sim 3 \times 10^{-10}$	B

* Certainty: A = Certain, B = Probable, C = Likely.

π Mesons

H. A. Bethe (Cornell) opened a session on π mesons with a general survey paper. He drew attention to the slope of the π-p scattering curve in the region 0-300 Mev, pointing out the rapid increase in cross section at low energies and the sharp maximum at about 150 Mev. The rapid rise indicates that P-wave mesons are chiefly concerned in the scattering, and he suggested that the maximum was a true resonance caused by a $T = {}^{3}/_{2}$, $P_{3/2}$ state. Bethe showed that the angular distribution curves for photoproduction and for π-p scattering were consistent with this view of the resonance.

At very much higher meson energies, about 1,000 Mev, a second maximum occurs in the π^{-}-p scattering cross section curve. The π^{+}-p curve does not show such a maximum, which must therefore be attributed to a $T = {}^{1}/_{2}$ state. The Tamm-Dancoff theory for $T = {}^{1}/_{2}$ gives the $D_{5/2}$ state as the first attractive state, and Bethe suggested that the second maximum was due to this, although he admitted that preliminary calculations on this state do not give a resonance.

A. M. Thorndike (Brookhaven) gave the figures on which Bethe's suggestions were based. With the Brookhaven cosmotron, measurements of π-p scattering have been made from 0.2 to 1.5 Bev. For positive mesons, σ_{total} drops to 27 millibarns at 0.45 Bev and is roughly constant at higher energies. However, for negatively charged pions, σ_{total} drops to about 25 mb, rises to 49 mb at 1.0 Bev, and drops again to 34 mb at 1.5 Bev.

Heavy Mesons and Hyperons

C. C. Butler (Imperial College, London) reviewed the heavy-meson and hyperon situation; it appears to have been clarified only little since the 1952 Rochester conference (*7*). As the relevant nomenclature is somewhat confused, it is worthwhile tabulating the data on the subject, as presented by Butler, extending somewhat the nomenclature adopted at the 1953 International Cosmic-Ray Congress held at Bagnères, France (*8*).

Light mesons, given the generic letter L, include the π mesons and all lighter ones. Thus the category at present includes only the π and μ mesons.

Heavy mesons, given the generic letter K, are those with a mass between that of the π meson and that of the proton. Several types are known, and the various modes of decay are given in Table 1.

Hyperons are particles with a mass greater than that of a proton. Once again, charged and uncharged hyperons exist, but the situation does not seem so confused as in the case of heavy mesons. Hyperons have the general symobl Y. Although this symbol is also used for the charged hyperons, with an appropriate sign, uncharged hyperons have the specific symbol Λ^{0}, a reminder of the $V_1{}^{0}$ notation used for these particles previously.

The hyperon family is listed in Table 2.

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How to Shield Reactor Beams

Neutron and gamma-ray absorption in boron-loaded paraffin and water was measured using a Hanford reactor beam as the source. Shielding design procedure based on these attenuation data is illustrated by an example

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EXPERIMENTAL FACILITIES using reactor beams require localized shields for personnel protection and background reduction. In the absence of a shielding theory based on microscopic nuclear cross sections, design procedure must be based on experimental measurements of the attenuation of beams of similar energy in similar geometry (*1*). Previous experiments do not entirely satisfy these criteria (*2–5*).

Data are presented here for absorption of a reactor neutron and gamma-ray beam in water and in boron-loaded water and paraffin. Five different ratios of hydrogen to boron are considered; in each case iso-flux lines are plotted to show the spatial distribution of thermal neutrons and gamma rays in a horizontal plane through the beam. In one instance a lead brick was placed in the beam to determine the extent of neutron scattering when lead is used as a shutter to eliminate gamma rays.

A design procedure based on attenuation curves derived from the flux distribution measurements is presented. It allows one to scale the results of this experiment to beams of similar geometry and energy distribution but different total intensity.

APPARATUS

A beam of neutrons and gamma rays from a Hanford reactor was used for this experiment. The beam was $1\frac{1}{2}$ in. in diameter at the interface where it entered the hydrogenous material 15 ft from the reactor. The thermal neutron flux as measured by bare and cadmium-covered gold foils was 7.4×10^6 n/cm²/sec.

Absorbers

A steel tank with a 3×3 ft bottom and 3.25 ft high was used to hold the water and the boric-acid solutions. The beam entered the tank through an aluminum window 10 in. in diameter. An air-filled Lucite tube $2\frac{1}{2}$ in. ID with $\frac{1}{16}$-in. Lucite windows allowed the beam to enter the solution 12 in. inside the tank. Four sets of measurements were taken in the tank: 1, with tap water; 2, with a lead brick suspended in water 12 in. from the front of the tank; 3, with 25 lb boric acid dissolved in the water (H/B = 456 where H/B represents the ratio of hydrogen atoms to boron atoms present in the solution); and 4, with 62 lb of boric acid dissolved in the water (H/B = 183).

To get lower H/B ratios two mixtures of paraffin and boron were used in stacked cardboard cartons. The first mixture (H/B = 10), obtained by adding just enough paraffin to saturate powdered boric acid, was 45% paraffin and 55% boric acid by weight. This mixture was cast in cartons $14 \times 10\frac{1}{2} \times 9\frac{3}{8}$ in. that were then stacked as shown in Fig. 1. Cracks between the cartons lowered the density from 1.18 gm/cm³ to a final average between 1.0 and 1.1 gm/cm³. A beam-entry hole 14 in. deep and $2\frac{1}{2}$ in. in diameter was drilled through the first carton. Eleven $1\frac{3}{4}$ in.-diameter holes for detectors were drilled 3 in. apart in line with the beam. Twelve holes 3 in. apart and arranged as shown in Fig. 1 were drilled left of the entrance hole.

The second mixture of paraffin and borax (H/B = 14) was cast in cartons $12 \times 12 \times 12$ in. Twelve of these were placed in a layer between top and bottom layers of the first mixture. Similar holes were drilled in this mixture.

Detectors

A BF_3 proportional counter primarily sensitive to thermal neutrons was used as the neutron detector. Its active volume was $\frac{3}{8}$ in. in diameter by 4 in. long. It was mounted in an aluminum tube with sufficient paraffin molded around it to make the assembly fit snugly inside the $1\frac{3}{4}$-in. diameter holes in the paraffin stack. Counter efficiency was measured by placing it in a known flux in a sigma pile; counts per minute were six times the n/cm²/sec ±50%.

A second BF_3 proportional counter placed inside the beam collimator shield was used to monitor number of neutrons striking the absorber per sec.

The gamma detector was a NaI(Tl) crystal mounted on an RCA-6199 photomultiplier. The detector was enclosed in a $1\frac{3}{4}$-in. OD aluminum container mounted on the end of a $\frac{1}{2}$-in. OD aluminum tube.

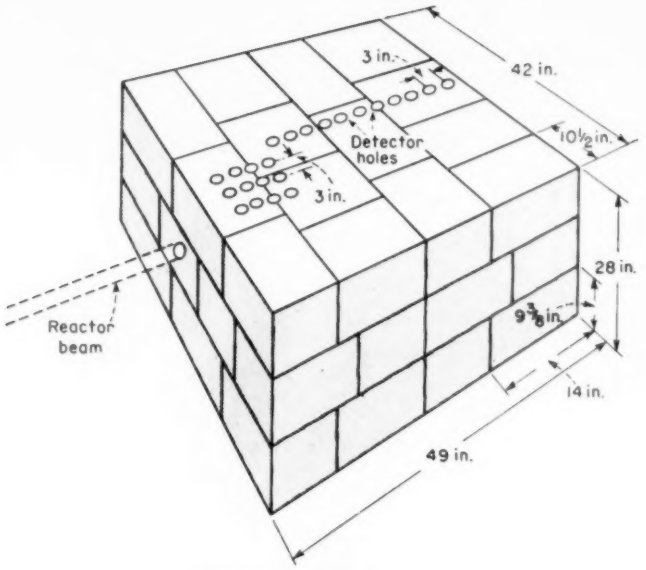

FIG. 1. Absorber used to determine neutron and gamma-ray attenuation in boron-loaded paraffin. Stacked cardboard cartons were filled with borax-paraffin and boric acid-paraffin mixtures

Photomultiplier current was measured with an electrometer. Electrometer linearity was confirmed within ±10% by comparing its readings for the current from a high-impedance source with those of a galvanometer and a microammeter. The variable high-impedance current source was provided by a photomultiplier with the dynode voltage and the amount of light striking the photocathode being variable.

Sensitivity of the gamma detector was adjusted so that readings in mr/hr could be taken directly from the instrument. The detector was calibrated using a source of known strength. The calibration measurements were made with an accuracy of 20% to make the over-all accuracy roughly 30%. Since the primary interest was relative intensities, more accurate absolute calibration of the detector was not attempted.

In the water tank the detectors were mounted on a ringstand. This ringstand stood on a piece of lumber that was placed across the tank parallel to the beam. The detectors were positioned by aligning the piece of lumber with marks spaced 3 in. apart on each edge of the tank and placing the ringstand on marks spaced 3 in. apart on the piece of lumber. Only one detector was in the tank at any one time.

In the paraffin mixtures the detectors were placed in the holes. To determine the flux distribution perpendicular to the beam these holes were moved across the beam. This was done by moving the dolly upon which the stack of cartons was mounted in 3-in. increments determined by marks on the floor at the front and rear of the dolly. The entrance hole was maintained in the same position relative to the beam by shifting cartons as required.

EXPERIMENTAL PROCEDURE

Neutron-flux data were recorded as the number of counts occurring in each position during the time the monitor took to reach a preset count of 25,600. This took approximately 1 minute.

Gamma-flux data were read from a meter that gave a steady reading for each position; therefore, the statistical error was less than the instrument error. Reproducibility was ±10%.

For each mixture the flux was determined throughout the horizontal plane containing the beam. Measurements were made every 3 in. along the beam and every 3 in. along perpendiculars to the beam at those points. Data were taken in a symmetrical pattern across the beam. Corresponding points on each side of the beam were averaged.

To extend tank measurements beyond 36 in., two sets of data were taken for each boron concentration: one with and one without the Lucite entry tube in position. The two sets of data were then normalized with respect to distance from the point of beam entry. Where the two sets disagreed, that set which was freer of wall effects was used.

Where the cracks between the cartons of paraffin caused experimental points to fall off a smooth curve, the data were discarded. This amounted to 25% of the points in the worst case.

RESULTS

Iso-flux contours are presented in Figs. 2–7. Comparison of Figs. 2 and 6 shows that thermal-neutron intensity in the beam is decreased a factor of ten by the addition of one boron atom for every ten hydrogen atoms in the shielding material. The slope of the lower part of the neutron attenuation curve differs little for the absorbers used in Figs. 2 and 6.

There was no significant change in gamma-ray flux distribution with increasing concentrations of boron. Thus there is no distinguishable effect caused by neutron absorption in boron rather than in hydrogen with its more energetic capture gamma ray.

Figure 7 shows the effect of suspending a 2 × 4 × 6 in. lead brick in the water in a position to intercept the beam. No appreciable effect on the neutron flux is evident, but the gamma-ray flux is strongly attenuated.

SHIELDING DESIGN

Figure 8 shows the attenuation of the neutron and gamma-ray beams in water along the beam and along the perpendicular to the beam at the point of entry. The curves have been extrapolated linearly past the range of experimental data.

One can use these curves for shielding design, remembering that the neutron beam strength was 8.4×10^7 n/sec and that cpm = 6 × intensity in n/cm²/sec ± 50%. One scales the neutron flux at any point by the ratio of the design beam strength to the one employed here. The beam gamma-ray flux is scaled by the ratio of the incoming beam intensity to the 4.5×10^4 mr/hr present here.

Since the number of scattering events is proportional not only to intensity but also to beam area, computations of gamma-ray flux perpendicular to the beam must include a factor relating the area to the 1.76-in.² beam used here.

Empirical Analysis

The design procedure can be based on algebraic relationships that present the data of Fig. 8 more accurately. The equations are formally similar to

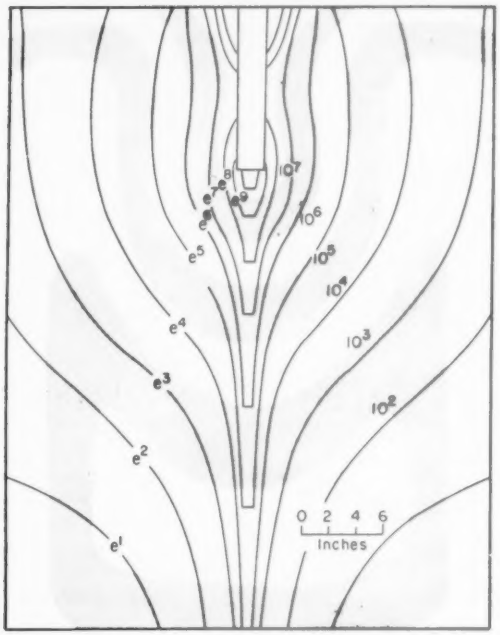

FIG. 2. Iso-flux curves in water. Edges of shaded areas correspond to contours of neutron intensity in cpm every decade. Solid lines are contours of gamma-ray intensity in mr/hr by integral powers of e

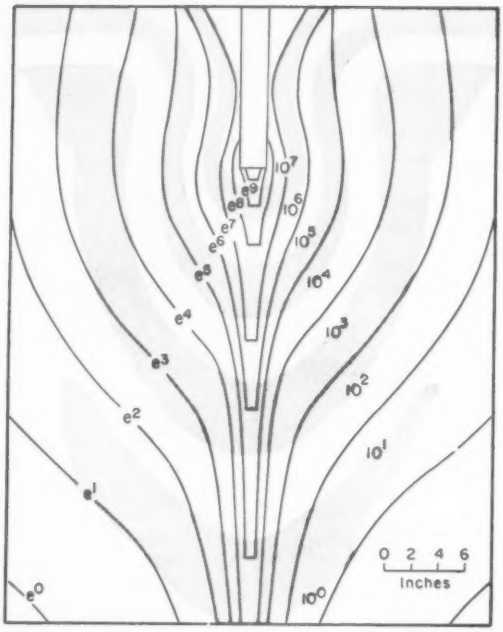

FIG. 3. Iso-flux curves in water-boric acid solution. H/B = 456, where H/B is the ratio of hydrogen atoms to boron atoms present in the solution

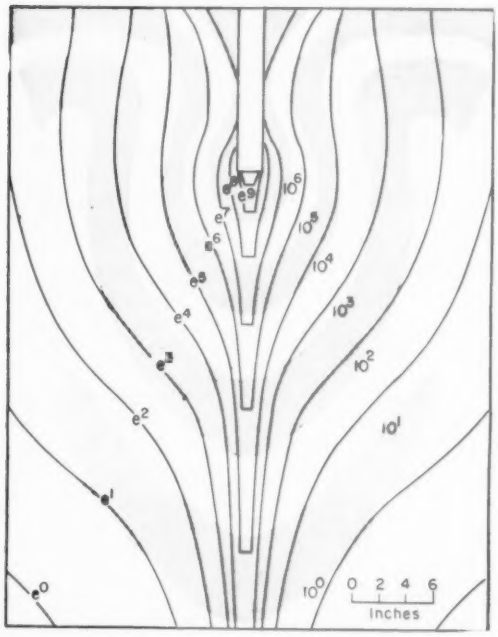

FIG. 4. Iso-flux curves for boric acid solution, H/B = 183

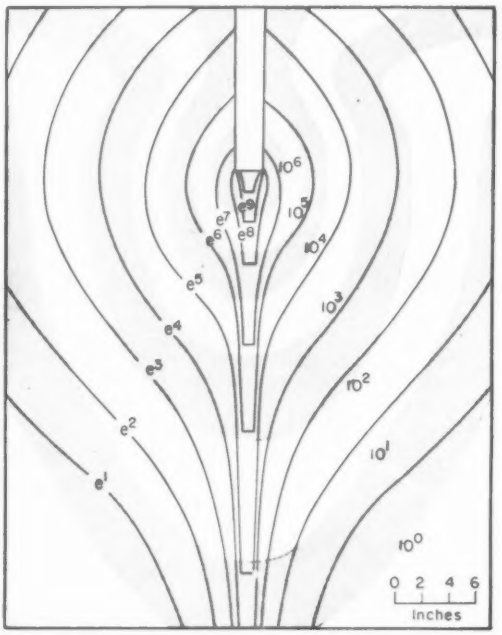

FIG. 5. Iso-flux curves in paraffin-borax mixture, H/B = 14

those describing attenuation in more ideal geometry, but their parameters are functions of the independent variable and are so plotted in Figs. 9–12.

The equations are

$$I = \frac{Sf_n}{4\pi R^2} e^{-R/L_n} \quad (1)$$

for the neutrons, and

$$I_\gamma = I_0 f_\gamma e^{-R/L_\gamma} \quad (2)$$

for the gamma rays in the beam. For the gamma rays perpendicular to the beam an additional factor $A/1.76$ is required to account for the change in beam area.

The preceding symbols have the fol-

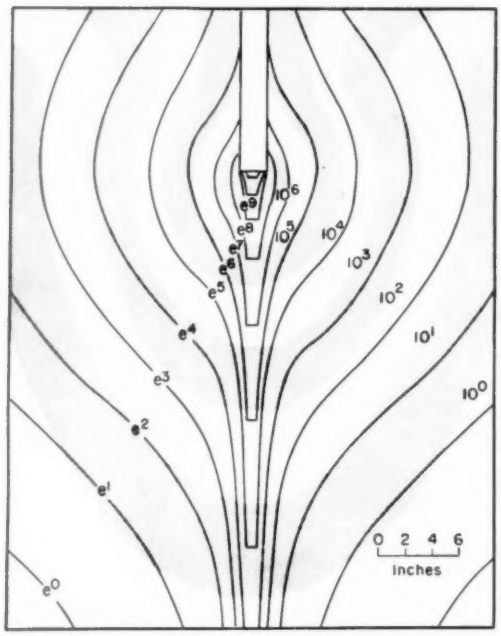

FIG. 6. Iso-flux contours in paraffin-boric acid mixture, H/B = 10

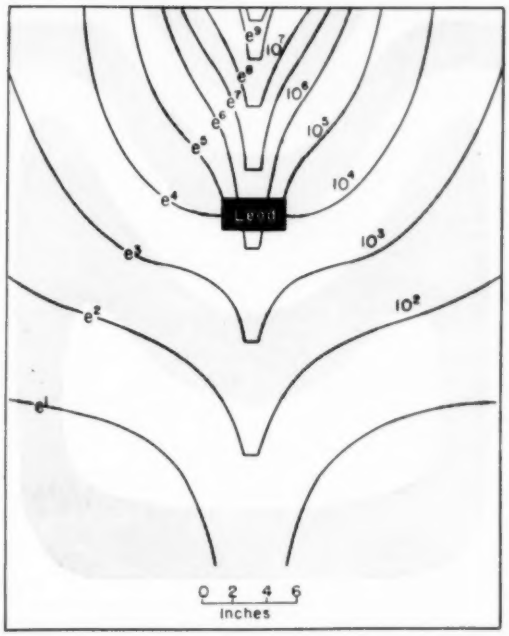

FIG. 7. Iso-flux contours in water with 2 × 4 × 6 in. lead brick in the beam. Note strong attenuation of the gamma rays, slight effect on neutrons

lowing meanings: S = beam strength in n/sec; I = neutron flux in n/cm²/sec; I_γ = gamma-ray intensity in mr/hr; L = relaxation length for a factor of $1/e$ (determined from the slope of Fig. 8) in in.; R = distance from the point of entry of the beam in in.; and A = beam area in in².

For the gamma rays, f is the ratio of initial intensity of gamma rays that penetrate a distance R to the intensity of the original beam. For illustration, the beam gamma-ray intensity 36 in. from the point of entry into the water is determined from Fig. 8 to be 45 mr/hr. Extrapolation back to 0 in. along the tangent to the curve at this point gives the intensity 2,050 mr/hr. Therefore f_γ for this point is $2{,}050/4.5 \times 10^4 = 0.0457$ since 4.5×10^4 is the intensity of the original beam.

The factor f for neutrons is that required to make Eq. 1 fit the experimental data. A conversion factor from in² to cm² is included in it; therefore f_n has the dimensions in²/cm².

For water f and L are plotted as functions of R in Figs. 9–12. No values are given for R less than about four beam diameters because the dependence on beam diameter is so strong there.

To find shielding dimensions necessary for a beam of neutrons and gamma rays, the dimensions for neutron shielding are found first. The amount that these dimensions will attenuate the gamma rays is calculated. The additional shielding necessary to attenuate the remaining gamma rays is then determined.

Example

Given a $1\frac{1}{2}$-in. diameter beam of 10^9 n/sec and 5×10^4 mr/hr of gamma rays; find the shielding dimensions for attenuation to 1 n/cm²/sec and 6 mr/hr.

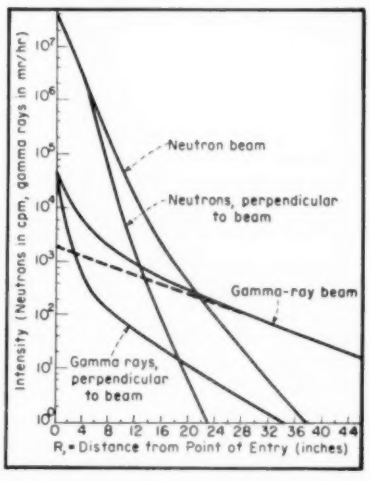

FIG. 8. Attenuation curves in water, for neutrons and gamma rays along and perpendicular to the beam

To find R from Eq. 1, a trial and error method is used. The graphical design procedure using Fig. 8 can be used as an aid in choosing the input value of R by taking the ratio $(8.4 \times 10^7)/10^9$ times the intensity to which it is desired to attenuate the beam: 0.084 n/cm²/sec.

This falls off the range of Fig. 2, but it can be extrapolated readily to give R = 41.7 in., which will be used for the first trial value.

Now, proceeding with the design: for R_1 = 41.7 in., L_1 = 3.9 in. from Fig. 9 and f_1 = 0.587 in²/cm² from Fig. 11, and therefore

$$I = \frac{(10^9)(0.587)}{4\pi(41.7)^2}\, e^{-41.7/3.9}$$

$$= 0.613 \text{ n/cm}^2\text{/sec}$$

Since this is low, calculate I again using R_1 = 41 in. Then L_1 = 3.9 in. and f_1 = 0.587 in²/cm²; thus one can obtain

$$I = \frac{(10^9)(0.587)}{4\pi(41)^2}\, e^{-41/3.9}$$

$$= 0.760 \text{ n/cm}^2\text{/sec}$$

This is still low, so try R_1 = 40 in., then L_1 and f_1 are unchanged and

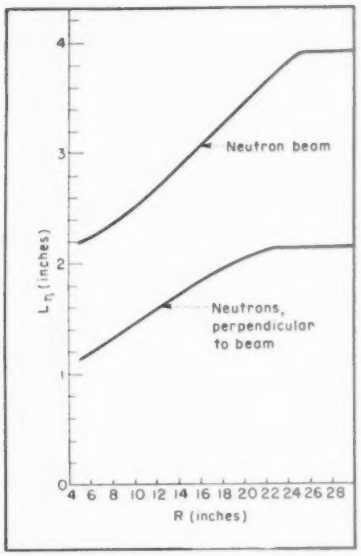

FIG. 9. Neutron relaxation length, L_n, in water

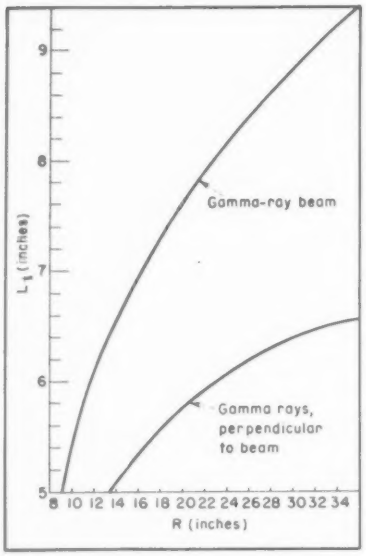

FIG. 10. Gamma ray relaxation length, L_γ, in water

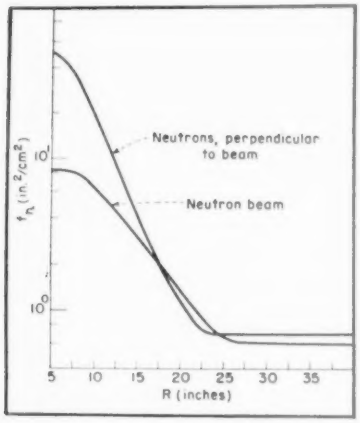

FIG. 11. Factor f_n for empirical analysis of neutron attenuation

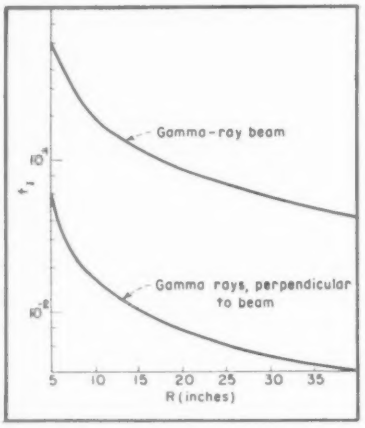

FIG. 12. Factor f_γ for empirical analysis of gamma-ray attenuation

$$I = \frac{(10^9)(0.587)}{4\pi(40)^2}\, e^{-40/3.9}$$

$$= 1.01 \text{ n/cm}^2\text{/sec}$$

This is near enough for practical purposes; in fact, the uncertainty in the original attenuation experiment makes this intensity uncertain to within 50%.

To find R in the direction perpendicular to the beam, the same procedure is used. For $R_2 = 24.5$ in., $L_2 = 2.13$ in. from Fig. 9, and $f_2 = 0.69$ from Fig. 11; then one obtains in similar fashion

$$I = \frac{(10^9)(0.69)}{4\pi(24.5)^2}\, e^{-24.5/2.13}$$

$$= 1.01 \text{ n/cm}^2\text{/sec}$$

Thus a cylindrical tank of water 49 in. in diameter and 40 in. long will provide the desired neutron attenuation. The age of neutrons in hydrogenous material is proportional to the density of the hydrogen (*6*). Paraffin contains $\frac{1}{8}$ again as much hydrogen as water per cm^3, hence the dimensions just calculated should be multiplied by $\frac{8}{9}$ to get the required dimensions of a paraffin shield: $R_1 = 40 \times \frac{8}{9} = 35.6$ in., length of paraffin shield; and $R_2 = 24.5 \times \frac{8}{9} = 21.8$ in. radius.

Equation 2 can be used to determine the attenuation of gamma rays through the paraffin since the difference between the gamma-ray attenuations of water and of paraffin is small. Thus, for $R_1 = 35.6$ in., $L_1 = 9.37$ in. from Fig. 10, and $f_1 = 0.047$ from Fig. 12, yielding

$$I = (5 \times 10^4)(0.047)\, e^{-35.6/9.37} =$$

$$52.6 \text{ mr/hr}$$

For $R_2 = 21.8$ in., $L_2 = 5.87$ in. from Fig. 10, and $f_2 = 0.0071$ from Fig. 12, yielding

$$I = (5 \times 10^4)(0.0071)(1.76/1.76)$$

$$e^{-21.8/5.87} = 8.7 \text{ mr/hr}$$

To reduce these gamma-ray levels to 6 mr/hr, the nearest approximation for practical use is to consider the energy of the gamma rays at this point as that corresponding to the relaxation length as given in Fig. 10. These are found to be 2.5 and 1.0 Mev. For iron $L_1 = 0.681$ and $L_2 = 0.862$ (*7*). Inserting these values in the usual exponential attenuation formula, $I = I_0\, e^{-x/L}$ we find $x_1 = L_1(-\ln I/I_0) = 0.681\ (-\ln 6.0/52.6) = 1.48$ in. of iron. Similarly $x_2 = 0.862\ (-\ln 6.0/8.7) = 0.43$ in. of iron.

From Figs. 2–7 it can be seen that backscattering occurs where the beam enters the material. To eliminate as much of this as possible, a hole at least 12 in. deep should be provided through which the beam can enter.

This shield would be a cylinder 44.5 in. outside diameter and 48.1 in. long closed at one end and made of $\frac{1}{2}$ in. steel. A 1-in. steel disk about 12 in. in diameter bolted to the closed end attenuates the gamma-ray beam that penetrates the paraffin with which the cylinder is filled. A hole wide enough to accommodate the beam is drilled 12 in. deep in the paraffin. This hole is in the open end of the cylinder so that a paraffin surface is presented to neutrons scattered from the beam.

* * *

The contribution of Dr. J. E. Faulkner in the preparation of this paper was considerable and is gratefully acknowledged. This work was supported by the Atomic Energy Commission.

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CROSS SECTIONS

Radioactivity in Animal Thyroids from Various Areas

By LESTER VAN MIDDLESWORTH
Department of Physiology
University of Tennessee
Memphis, Tennessee

TABLE 1—Radioactivity in Fresh Animal Thyroids (μc I^{131} per Gram of Thyroid)

	Place slaughtered	Origin of animals	Species	Date	Animal number	Thyroid tissue: Wt. (gm)	Thyroid tissue: $\mu c/gm \times 10^3$	I^{131} standard ($cpm/\mu c \times 10^{-4}$)
A	Memphis, Tenn.*	Unknown	Cattle	June 12	1	7.0	4.0	10.0
					2	11	3.0	
					3	7.7	4.4	
					4	3.5	2.3	
				June 14	5	19	0.4	10.0
					6	4.0	2.7	
					7	3.0	1.7	
					8	4.0	2.2	
					9	0.7	2.1	
B	San Francisco, Calif.	West of Oklahoma	Cattle	June 16	10	10	0.60	19.9
					11	7.0	0.51	
					12	10	0.42	
					13	7.0	0.40	
					14	5.0	0.22	
					15	9.0	0.13	
					16	13	0.14	
					17	11	0.23	
					18	15	0.07	
					19	20	0.65	
C	Boston, Mass.	Local (?)	Cattle	June 30	20	15	0.15	4.47
					21	13	0.07	
					22	4.0	0.07	
					23	7.0	0.11	
					24	6.7	0.06	
					25	6.8	0.23	
					26	11.5	0.19	
					27	2.8	0.28	
					28	10.5	0.11	
					29	4.0	0.20	
					30	5.2	0.15	
					31	4.1	0.29	
					32	1.7	0.40	
D	Boston	Florida	Cattle	July 2	33	4.7	0.55	4.47
					34	3.7	1.30	
					35	5.5	1.33	
					36	4.3	0.72	
					37	1.7	0.16	
					38	1.0	0.68	
					39	1.8	1.11	
E	Boston	Kentucky	Lambs	July 2	40	0.8	0.87	4.47
					41	1.5	0.80	
					42	1.8	0.44	
					43	2.0	0.95	
					44	1.7	0.06	
F	Boston	Unknown	Sheep	July 2	45	0.7	1.9	4.47
					46	0.5	1.8	
					47–50 (pooled)	6.3	0.5	
					51–54 (pooled)	5.8	0.7	

*After 6.7 I^{131} half-lives, thyroid activity of 4 beef cattle, slaughtered in Memphis August 4, was about 1×10^{-3} μc I^{131} per gm of thyroid.

The thyroids of cattle and sheep slaughtered, during the period June 12 to July 2, 1954, in Memphis, San Francisco, and Boston contained significant amounts of radioactivity with a half-life of approximately 8 days.

Methods

One lobe of the thyroid was removed from 39 freshly slaughtered beef cattle, 5 lambs, and 10 sheep. Most of the beef glands were damaged as the animals were decapitated. The intact glands averaged approximately 10 gm per lobe. The radioactive determinations were made the day the animals were slaughtered.

The lobe or fragment was weighed, inserted in a $\frac{1}{2}$-oz ointment cup or beaker and placed as close as possible to a scintillation counter crystal. The gamma radioactivity was recorded. A counting standard was prepared from 0.1 μc I^{131} in a similar ointment cup or beaker. The radioactivity of the thyroid was expressed as μc/gm of thyroid tissue.

Since different counting equipment was used in the three cities, a new standard was prepared for each counter. In Memphis, the standard was prepared from I^{131} solution standardized by Abbott Laboratories. In Boston and Berkeley, the Oak Ridge calibration was accepted as correct.

Twelve grams of nonthyroid neck tissue from each of four animals were similarly counted and found to be free from detectable radioactivity. The energy of I^{131} γ-rays was compared with that from several thyroid specimens by placing a thin lead sheet between the counter tube and sample. The half-life was determined on high-counting specimens by recounting after approximately 8 days.

Data

Table 1 lists measurements made on sheep and cattle thyroid samples col-

lected in various areas of the United States.

The most radioactive specimen in group A counted 3,400 cpm or 42 times background. The average for the group was 16 times background. A thin lead plate absorbed 46% of the radiation from sample 3 and 47% of the I^{131} standard. After 8.3 days, the sample-3 decay factor (cpm June 12/cpm June 20) was 0.49 (the I^{131} factor is 0.485). These data strongly suggest that the radioactivity was due to I^{131}.

The counting efficiency was greatest on the instrument used for the group B determinations. The activity ranged from 32 to 2.5 times background (total atmospheric plus instrumental backgrounds). Sample 18 may have contained no I^{131}.

The counting efficiency of the equipment used for groups C–F was less than that used in Berkeley or Memphis, and the background was higher.

The group C activity was 1.5–2 times background. Specimens 21, 22, and 24 may have contained no I^{131}.

The animals of group D were said to be wild range cattle. They showed more radioactivity than the animals from the Boston area; the activity was 3.8–1.5 times background. Sample 35 was tested for the radiation energy by penetration through a lead sheet; the tissue radiation showed an absorption of 28% and the I^{131} standard showed an absorption of 26%. After 8 days, only one-half of the original activity of sample 35 was present.

The lambs of group E were believed to have been raised in Kentucky; their thyroids were intact but quite small. The radioactivity was only 1.7–1.3 times background. Sample 44 may have been free of I^{131}. However, when all 7 glands were pooled and counted together, the radioactivity was 2.6 times background in the 7.7-gm sample.

Two of the lobes of group F were counted separately and the remainder in groups of 4, then all 10 were pooled and counted. The counts were 4–1.4 times background. The decay rate of the 10 pooled thyroids was the same as the I^{131} standard.

Discussion

Most of these studies were made during an interval of approximately three I^{131} half-lives. Except for group D, radioactivity was less with each successive collection. This could have been due to coincidental biological differences, coincidental differences in distribution of I^{131}, progressive radioactive decay, or a combination of factors.

TABLE 2—Activity Corrected for Decay

Group and species	*Average observed* $\mu c/gm \times 10^3$	*Hypothetical* $\mu c/gm \times 10^3$ *(6/12/54)*
A, cattle	3.4	3.4
	1.8	2.1
B, cattle	0.29	0.42
C, cattle	0.17	0.89
D, cattle	0.79	4.4
E, lambs	0.62	3.4
F, sheep	0.70	3.9

To evaluate the factor of radioactive decay, Table 2 was prepared by correcting all the activities to the date of the original observation (June 12, 1954). It is not possible to conclude from these data whether or not the radioisotope was from a common source. As far as the author is aware, nuclear fission is the most likely source of this radioactivity.

If, for purposes of estimating total-body I^{131}, the following assumptions are made: (a) thyroids of the cattle contained approximately 20–90% of the total-body iodine (*1*), depending upon whether the average iodide intake was low or high, respectively, (b) the specific activity of all the body iodide was the same as the thyroid, and (c) the average weight of the undamaged thyroids of group A was 20 gm, then the average body I^{131} in the cattle of group A on June 12 would have been 0.34 μc if the average carrier I^{127} intake had been low or 0.07 μc if the I^{127} intake had been relatively high. The lower amounts of I^{131} found in the other animals resulted from individual differences and from radioactive decay.

Cattle and sheep ingest large amounts of foliage of low iodide (I^{127}) content, which should result in greater accumulation of the daily dietary iodide in the thyroid of cattle than would occur in carnivorous animals.

It has been suggested (*2*) that up to 0.3 μc of I^{131} (maximum permissible amount) could be maintained continuously in the human body without radiation hazard. However, due to a lack of data, it is not possible to correlate the I^{131} content of human beings with that of cattle. The data presented here do not indicate a radiation hazard to human beings or to animals.

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* * *

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Radiogold Administration

By D. L. TABERN

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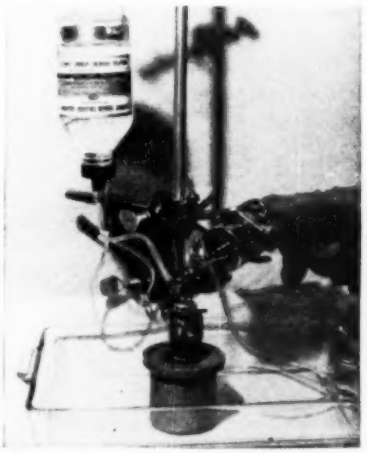
Exactly calculated dosages of radiogold colloid, from a "single-dose" or "bulk" shipment, can be administered into the pleural and peritoneal cavities by the improved gravity-infusion method* described here.

Sterile colloid is withdrawn from the shipping vial into a 5/8-in.-lead-shielded syringe (American Cystascope Makers, New York); radiation at the shield sur-



RADIOGOLD gravity-infusion set up

* D. L. Tabern, G. I. Gleason, R. G. Leitner, NUCLEONICS **10**, No. 2, 63 (1952).

face is 40–50 mr with a 100-mc dose. The syringe plunger is operated by a knob, actuating a sliding bar; the bar is calibrated to indicate the volume. A locking device on the syringe permits delivering the desired volume.

A 10-cm³ bacterin vial, with aluminum-sealed silicone-rubber stopper, is set up in a lead shield having ½–¾ in. walls. A needle inserted through the stopper supplies saline from a Venopack infusion set (silicone rubber permits insertion without applying pressure). A second needle, reaching to the bottom of the vial, is connected directly to the pleural or peritoneal cavity. Infusion is started. When all seems to be operating properly, the syringe needle is inserted through the stopper. The syringe barrel is slipped into a clamp, which keeps the actuating wheel outside the vial's radiation field. A bent needle facilitates this by allowing the syringe to be inclined at 45 deg.

Since the volume delivered per fractional turn of the knurled syringe wheel may be as small as 0.1 cm³, any dilution can be achieved by properly timing the injections. The operator need be near the syringe only during brief moments required for turning the wheel.

The syringe, still in place, is washed out by alternate filling and emptying with saline wash. If, at the end of infusion, sufficient air is forced into the vial, it is left essentially activity-free and empty.

Shielding for the vial need not weigh more than 30 lb. All tubing is disposable and, with this stopper, inexpensive needles suffice. The cost of discarded contaminated equipment is about $2.

Dose Received by Thermal Neutron Treated *Drosophila Melanogaster*

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In calculating the biological effect of thermal neutrons, tissue ionization is attributed to the summation of capture and decay radiations. Thus, the radiation dose is a function of the elementary composition and geometry.

In most thermal-neutron capture reactions, the capture radiation consists of γ-rays. Three exceptions are $N^{14}(n,p)C^{14}$, $B^{10}(n,\alpha)Li^7$, and $Li^6(n,\alpha)H^3$. In these cases, the available energy of 0.6, 2.4 and 4.6 Mev, respectively, is distributed between the recoiling nucleus and the emitted particle. The $Cl^{35}(n,p)S^{35}$ reaction can be disregarded because of its low cross section.

Tissue analyses of *Drosophila melanogaster* adults (Table 1) were generally made on samples containing both sexes. Where separate male and female analyses were made, both data are given. The latter analyses were greatly facilitated by special breeding systems that produced solely male or female offspring. Female offspring were produced by the cross y sc^4 InSc^{81} (bb df)/ClB females × $X.Y^S/Y^{LC}$ (bb df) males; male offspring from yf: = (bb df)/Y females × $X.Y^S/Y^{LC}$ males. Data are also given for flies undergoing their entire development upon boron- or lithium-enriched media—"standard" medium (*5*) to which H_3BO_3 or LiCl was added to give 0.005*M* concentrations. This increased boron and lithium content of flies by factors of 100 and 2, respectively.

Calculations

The methods of calculation follow closely those used by Curtis and Teresi (*7*). R_T, the total thermal-neutron capture reactions for a given element, is given by $R_T = t_1 f \sigma N_T$ where t_1 = the time of exposure to thermal neutrons in seconds; f = the thermal neutron flux (n_{th}/cm²/sec), assuming that the flux is uniform throughout the insect and equal to the flux in air; σ = the reaction cross section in barns (1×10^{-24} cm²). N_T, the number of target atoms per gm of tissue, is given by

$$N_T = N_{av} AP / A_w \times 10^4$$

where N_{av} = Avogadro's number = 0.602×10^{24}; A = the natural abundance (%) of the target isotope in the element; P = the abundance (%) of the element per unit weight of tissue; A_w = the atomic weight of the element.

N^*, the number of radioactive atoms (resulting from a given capture reaction) present upon removal from the pile, is given by

$$N^* = N_T f \sigma (1 - e^{-\lambda t_1}) / \lambda$$

where λ = the disintegration constant of the radioactive daughter = $0.693/T_{1/2}$ and $T_{1/2}$ = the half-life.

Q, the total disintegrations occurring per gram of tissue during thermal neutron exposure t_1 and during an interval t_2 after exposure (disregarding biological excretion), is given by $D_1 + D_2$, where D_1 = disintegrations occurring during exposure = $R_T - N^*$, and D_2 = disintegrations occurring after exposure = $N^*(1 - e^{-\lambda t_2})$.

R_D, the radiation dose in rep (roentgens equivalent physical) due to a given capture reaction, is given by

$$R_D = R_T E F / Z$$

where E = the energy (ev) available from the capture reaction, F = the fraction of the liberated energy absorbed by the fly, $Z = 58.1 \times 10^{12}$ = the number of electron volts liberated per gram of tissue by 1 rep.

Capture-Radiation Dose

R_T values for doses of 1×10^{13} n_{th}/cm² are given in Table 1. H^1, N^{14}, Cl^{35}, and K^{39} are responsible for the majority of the capture reactions within the fly.

The important capture reactions occurring in adult *Drosophila* and *Tradescantia* buds, where data of a similar nature exist (*8*), are compared in Table 2. The value of 0.00429×10^{24} given in Table 6 of Conger and Giles' paper (*8*) for the number of N atoms per cm³ is in error and should read 0.000427×10^{24}. This correction explains the difference between the values shown in Table 2 and those found in the latter paper (H, 72%; N, 26%; etc.). The $B^{10}(n,\alpha)Li^7$ reaction is important in *Tradescantia*, but not so in *Drosophila*, whereas $N^{14}(n,p)C^{14}$ acts inversely.

Calculation of R_D values for *Drosophila* are presented in Table 3. F values of 1.0 are used in the case of alpha- and proton-emitting reactions. An F value of 0.00091 was calculated for the $H^1(n,\gamma)H^2$ reaction. This follows from substituting 0.025 cm^{-1} for α, the linear absorption coefficient, for

TABLE 1—Composition and Capture Reactions of *Drosophila* Tissue

Isotope	Isotopic Abundance (%)	Elementary composition of tissue* (% wet weight)	$\sigma(6)$ (barns)	N_T	$R_T(1 \times 10^{13} N_T \sigma)$	Radioactive daughter	$T_{1/2}$
H^1	99.98	10.4(m) 9.1(f)†	0.330	5.43– 6.21×10^{22}	1.71– 2.05×10^{11}		
Li^6	7.30	0.0002 0.00039(m)‡ 0.00032(f)‡	910	1.27×10^{16}	1.16×10^{8}		
B^{10}	18.83	<0.000015 0.0015‡	3,990	1.57×10^{15}	6.26×10^{7}		
N^{14}	99.62	4.2 (3)	1.70	1.80×10^{21}	3.06×10^{10}		
Na^{23}	100	0.120 (1)	0.49	3.14×10^{19}	1.54×10^{8}	Na^{24}	15 h
P^{31}	100	0.314 (5)	0.19	6.10×10^{19}	1.15×10^{8}	P^{32}	14.30 d
Cl^{35}	75.4	0.056(m) 0.049(f)	40	0.63 0.72×10^{19}	2.51– 2.88×10^{9}	Cl^{36}	4.4×10^{5} y
Cl^{37}	24.6		0.56	2.05– 2.34×10^{18}	1.15– 1.31×10^{7}	Cl^{38}	37.3 m
K^{39}	93.18	0.445 (2)	1.87	6.38×10^{19}	1.19×10^{9}	K^{40}	1.3×10^{9} y
K^{41}	6.82		1.19	4.67×10^{18}	5.56×10^{7}	K^{42}	12.4 h
Cu^{63}	68.94	0.0002 (4)	4.3	1.31×10^{16}	5.63×10^{5}	Cu^{64}	12.8 h
Cu^{65}	31.06		2.11	5.88×10^{15}	1.24×10^{5}	Cu^{66}	5.1 m

*Analyses made in BNL chemistry department: chlorine and lithium (Dr. R. W. Stoenner), boron (Mr. Morris Slavin), and hydrogen (Miss Nancy Day).
† m = male, f = female.
‡ Fed upon enriched medium (see text).

2.2-Mev γ-rays (*9*) and 0.0371 cm for p_m, the mean path of an H-capture γ-ray in the *Drosophila* abdomen (*10*), in the equation $F = 1 - e^{-ap_m}$. The entire energy of the 1,300-ev recoiling deuteron in the $H^1(n,\gamma)H^2$ reaction (*11*) is absorbed in tissue. The 12-rep R_D for the H-capture reaction is made up of a 7-rep contribution from the capture γ-rays and 5 rep from the recoiling deuterons.

If the majority of tissue capture reactions are due to hydrogen, but only 3.5% of the total capture-radiation dose are ascribable to hydrogen, then all other γ-emitting capture reactions contribute negligible amounts to the total absorbed dose. Consequently nitrogen-capture protons are responsible for the majority of the ionization in tissue due to neutron-capture radiations.

Decay-Radiation Dose

Decay curves were determined for groups of 100 male or female flies exposed for 1.5 or 24 hr to a thermal neutron flux of 6.5×10^8 $n_{th}/cm^2/sec$. No marked differences were noted between sexes after corrections were made for sample weights. A "curve-peeling" analysis revealed phases of approximately 0.5-hr, 3-hr, 0.5-day and 14-day half-life. It is believed that these phases represent, respectively, Cl^{38}; Mn^{56}; a mixture of Na^{24}, K^{42}, and Cu^{64}; and P^{32}. From the sodium, potassium and copper content of the flies, sodium should account for the majority of 0.5-day half-life radioactivity, potassium giving 0.5 the sodium count and copper giving 0.01 the potassium count.

A Q value was calculated for Na^{24}, since it is the most abundant of the short half-lived isotopes formed during thermal neutron treatment. It was found that 71% of all Na^{24} atoms formed by a 5-hr dose of 1×10^{13} n_{th}/cm^2 have decayed by one day following removal from the reactor. The major Na^{24} β-ray has a maximum energy of 1.39 Mev and a calculated average absorption coefficient (α) of 5.32 cm^{-1}, using $\alpha = 8.8/E_{max}^{1.53}$ (*12*). R, the dose in rep absorbed by the organism from β-radiation from a specified decaying radioisotope, is given by

$$R = QE_{av}F/Z$$

where E_{av} = the average energy of the emitted β-particle = $E_{max}/3.5$; E_{max} = the maximum β-particle energy. R calculated for Na^{24} is 0.13 rep. Since this dose is negligible, β-radiation from radioisotopes of similar or longer half-lives than Na^{24} may be disregarded.

Short half-life Cl^{38}, produced in smaller quantities than Na^{24}, undergoes almost complete decay. The maximum energies of two of the three Cl^{38} β-particle spectral distributions are greater than the E_{max} for Na^{24}. Thus, Cl^{38} produces a negligible radiation dose, because of its small amount and because a smaller fraction of the β-ray energy would be absorbed in *Drosophila* tissue than in the case of Na^{24}.

Since decay radiations contribute a negligible radiation dose to treated flies, it is evident that protons from nitrogen capture reactions are the physical basis of the biological effects of thermal neutrons in adult *Drosophila melanogaster*.

* * *

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TABLE 2—Comparison of Reactions

	Tradescantia	*Drosophila*
$H^1(n,\gamma)H^2$	94.9%	84.7%
$N^{14}(n,p)C^{14}$	3.4	12.6
$Cl^{35}(n,\gamma)Cl^{36}$	0.7	2.1
$B^{10}(n,\alpha)Li^7$	0.5	
$K^{39}(n,\gamma)K^{40}$	0.4	0.5
	99.9%	99.9%

TABLE 3—Capture-Radiation Doses to Adult Drosophila (1×10^{13} n_{th}/cm^2)

Reaction	*Dose (rep)*
$N^{14}(n,p)C^{14}$	316 (92.9%)
$H^1(n,\gamma)H^2$	12 (3.5%)
$Li^6(n,\alpha)H$	9 (2.7%)
$B^{10}(n,\alpha)Li^7$	3 (0.9%)
Total	340

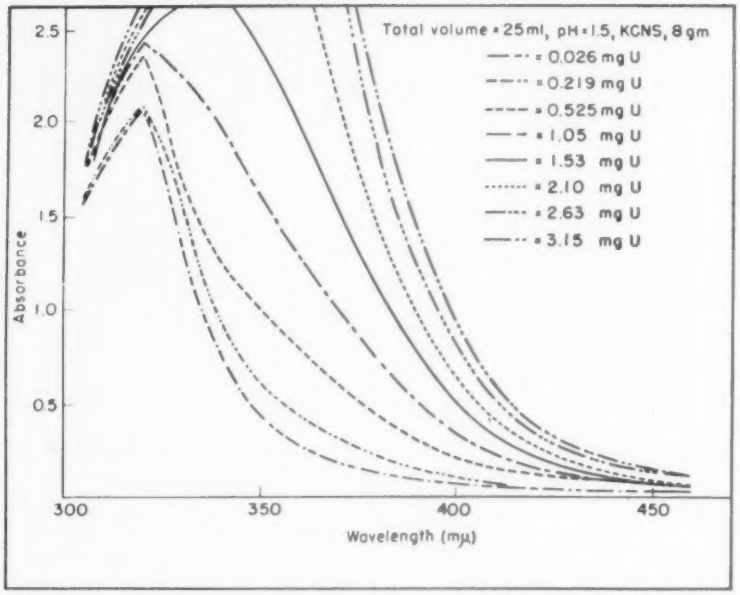


FIG. 1. Spectrophotometric curve of uranium thiocyanate in pentaether

Photometric Determination of Uranium in Thorium

By LOUIS SILVERMAN
and LAVADA MOUDY
North American Aviation, Inc.
Atomic Energy Research Department
Downey, California

Determination of uranium in thorium metal alloys and salts is of interest since uranium is found in thorium ores and is used in conjunction with thorium in special processes.

Currah and Beamish* found that thorium interfered in the photometric determination of uranium as thiocyanate in aqueous medium. They compensated for the thorium interference by drawing a standard curve for thorium-uranium mixtures.

This paper describes how extracting uranium into a nonaqueous solvent not only concentrates the uranium into a smaller volume, but reduces thorium interference to about 1% of the uranium content.

* J. E. Currah, F. E. Beamish, *Ind. Eng. Chem.* **19**, 609 (1947).

Extraction and Photometric Materials

Reagents

Hydrochloric acid—c.p., specific gravity 1.19

Pentaether—dibutyl ether of tetraethylene glycol, $(C_4H_9OC_2H_4OC_2H_4)_2O$; keep metallic tin in contact with reagent; reagent supplied by Carbide and Carbon Chemical Co. and labeled "dibutoxy tetraglycol"

Pentaether-stannous chloride mix—pentaether saturated with stannous chloride solution; keep metallic tin in contact with solution

Potassium hydroxide solution—30 gm dissolved in 100 ml water; keep in polyethylene container

Potassium thiocyanate—c.p.

Stannous chloride solution—35 gm $SnCl_2 \cdot 2H_2O$ dissolved in 100 ml 20% hydrochloric acid solution; keep metallic tin in contact with solution; once a week, boil solution in contact with tin

Uranium standard solutions—uranyl nitrate, chloride, sulfate or perchlorate solutions, standardized by gravimetric method; stock solutions contain 0.1, 1, 10, 100, and 1,000 μg/ml

Apparatus

Beckman Model DU Spectrophotometer—without special attachments
10-mm corex or silica cuvettes

Procedure

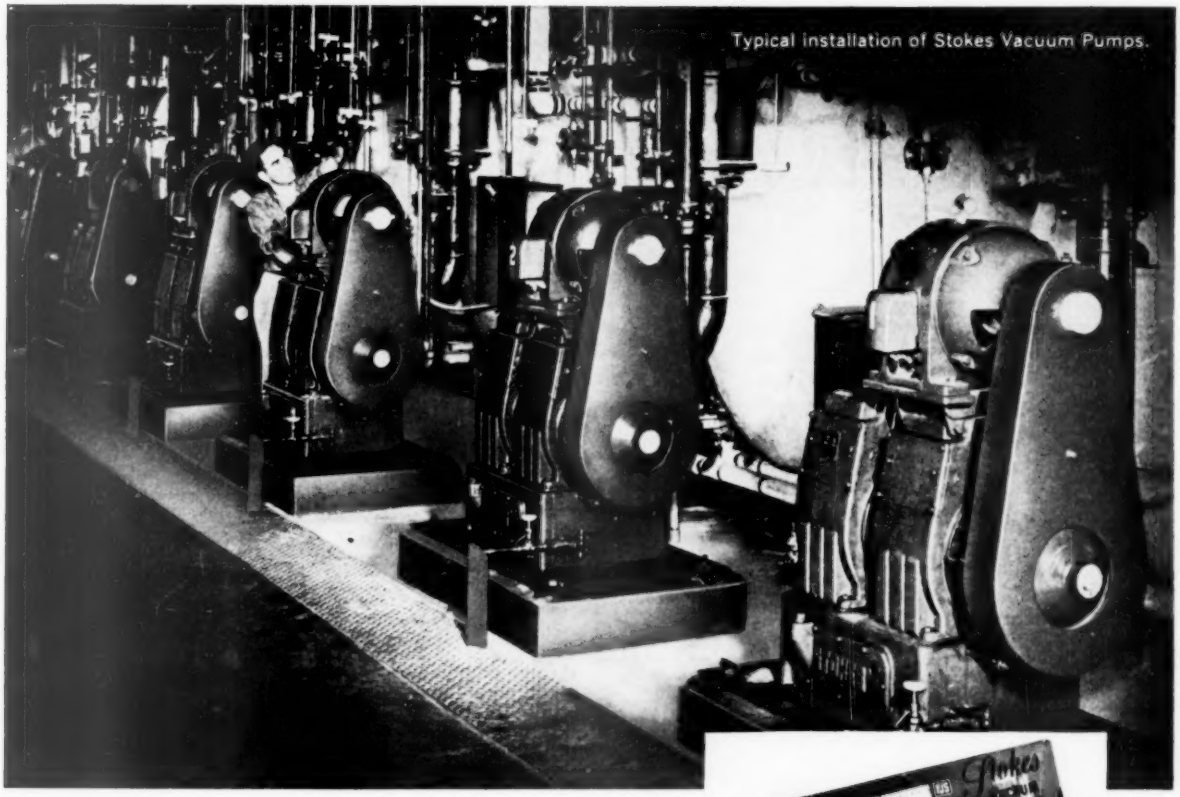
Transfer the sample to a 150-ml beaker and dilute to about 40 ml with water. Add sufficient hydrochloric acid to make the solution about 10% acid, by volume. Add 8 gm of solid potassium thiocyanate and mix. The solution is usually red at this point (ferric ion); add stannous chloride solution, dropwise, until the red color disappears, then one drop in excess. Adjust the *p*H to 1.5 with potassium hydroxide solution, then transfer the uranium solution to a 125-ml Kimble Glass separatory funnel.

Measure into the funnel 21 ml of pentaether and 2 ml of pentaether-stannous chloride mix, if the expected uranium content is 0.1–3.5 mg; use 9 ml of pentaether and 1 ml of the mix if the expected uranium content is 0.02–0.1 mg (4 ml of the ether plus 1 ml of mix may be used for the detection of microgram quantities of uranium). Shake the solutions for 30 sec and let stand until the aqueous layer is nearly clear (about 5 min), then drain off the lower (aqueous) layer. Dry the inside of the stem of the funnel with absorbent tissue. Filter the yellow or pink organic layer through dry No. 1 Whatman filter paper into a 25, 10 or 5 ml volumetric flask, using clear pentaether as wash liquid to fill the volumetric flask to the mark. Mix. The faint pink color fades to the proper yellow color in 1–2 hr.

After the mix has stood 2 hr (preferably in a thermostat at 25° C), read the optical density at the selected wavelength and obtain the uranium content from the calibration curve.

Note: Glassware should not be rinsed with acetone, since acetone intensifies the red color extracted into the pentaether.

Calibration curves preparation. Prepare a series of 150-ml beakers containing 40 ml of water. Pipette in known amounts of uranium (0.01–3.5 mg) and follow the technique described in the procedure. It is suggested that spectrophotometric curves be run for several concentrations of uranium, from 420 to 330 mμ, for example, to familiarize the analyst with the optical density changes inherent in the uranium-thiocyanate system. Straight-line graphs should be obtained for all wavelengths between 360 and 420 mμ.



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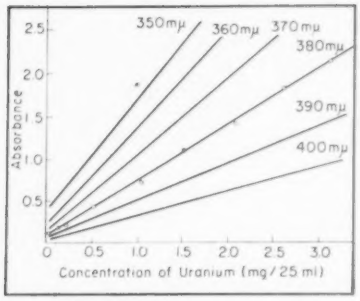

FIG. 2. Absorbance curve of uranium thiocyanate in pentaether

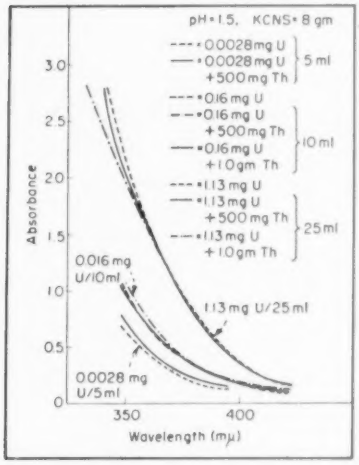

FIG. 3. Spectrophotometric curve of uranium thiocyanate in pentaether

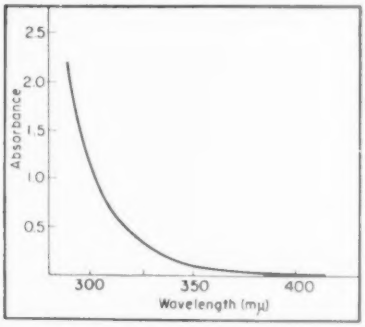

FIG. 4. Absorbance curve of pure pentaether; water as blank

(Uranium solutions fluoresce at the lower wavelengths.)

Results and Discussion

Spectrophotometric curves for uranium thiocyanate (0.026–3.15 mg) in pentaether are shown in Fig. 1, and the standard absorbance-concentration data obtained from Fig. 1 are replotted in Fig. 2. Either the 370 or 380 mμ curve may be selected as the standard calibration plot.

Figure 3 contains three sets of uranium-thorium spectrophotometric curves. The 1.13-mg-uranium curves, with and without thorium, are nearly coincident in the 370–410 mμ range; a variation of not more than ±0.01 mg per 1.13 mg of uranium is to be expected in the presence of 1 gm of thorium. The volume of solvent is 25 ml.

When the amount of uranium present is only about 15 μg (Fig. 3), the volume of pentaether is reduced to 10 ml, and the expected error is about 1 μg. If the uranium is less than 5 μg, the extractant is reduced to 5 ml, but the reproducibility is about 0.5 μg.

Not more than 2 mg of iron may be present. Although aqueous stannous chloride reduces large amounts of ferric chloride in aqueous solution, the reduction is not at all complete and the subsequent pentaether extract is pink. If not more than 2 mg of iron are present, then the pink extract changes to the uranium thiocyanate yellow after about 1 hr. At the same time the uranium color becomes steady, and attains a stable state. The absorbance should be read at the end of 2 hr, and begins to increase after 3 hr of standing.

The spectrophotometric curve of the extractant, pentaether, is shown in Fig. 4. It is suggested that pentaether be used as the reference solution, although water may be used when the calibration curve is made up in similar fashion.

* * *

This article is based on studies conducted for the Atomic Energy Commission under contract AT-11-1-Gen-8.

Gamma-Ray Dosimetry with Cellophane-Dye Systems

By ERNEST J. HENLEY
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New York, New York

The complexities of electronic measurements and the limitations of the photographic films have contributed greatly to the increasing interest in chemical dosimetry.

Some of the chemical systems that have been recently suggested and actually calibrated with some degree of care include: (a) oxidation-reduction dyes in agar (*1, 2*); (b) benzene, sodium benzoate in water (*3*); (c) polymerizations of various monomers (*4*); (d) methylene blue dyes in water (*5, 6*); (e) phosphate glass (*7*); (f) depigmentation of rats (*8*); (g) polyvinyl chloride films (PVC) (*9*); (h) ferrous-ferric oxidation in 0.8*N* H_2SO_4 (*10, 11*); and (i) ceric-cerous reduction in 0.8*N* H_2SO_4 (*11, 12*).

For monitoring radiation sterilization of food, cost and convenience are the chief criteria. Of the nine dosimeters proposed, only the polyvinyl chloride films and phosphate glass merit consideration.

Since the manufacture of PVC films is difficult, the author surveyed commercially available materials that could be used as a monitoring device. Moistureproof, heat-sealable cellophane, containing a dimethoxy-diphenyl-disazo-bis-8-amino-1-naphthol-5,7-disulphonic acid dye (*13*) proved to be most suitable. The sheets cost 0.042¢ per 1,000 in^2, and the optical and physical characteristics are satisfactorily uniform for use as a control device.

The techniques used in handling the dosimeters present no unusual problems. Sheets of the cellophane are cut into strips $^1/_2$ in. wide and $1^3/_4$ in. long. They are then inserted into an aluminum holder (Fig. 1), especially constructed to fit into the standard Beckman cell holder, and the initial transmission of the dye is then read. Thorough scanning of the absorption spectrum in the visible region showed that the most suitable peak was at 6,550 Å; all subsequent readings were made at 6,550 Å on a DU Model Beckman spectrophotometer at a slit width of 0.15. The thickness of commercial

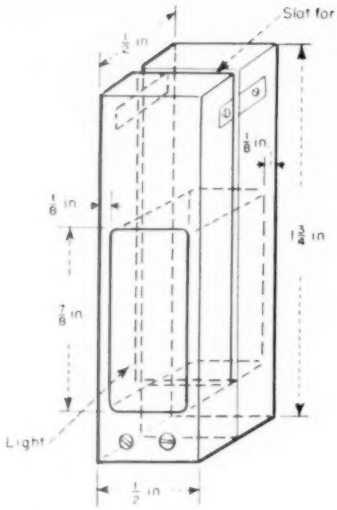

FIG. 1. Aluminum holder

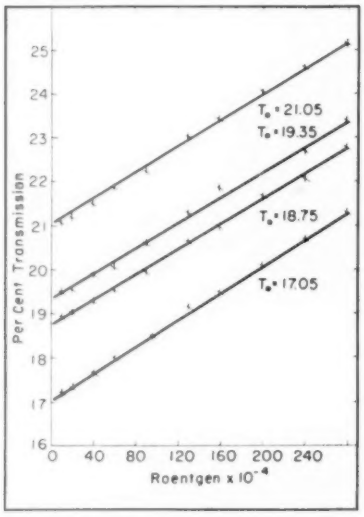

FIG. 2. Transmission vs dose for several initial film readings

cellophane is satisfactorily controlled at 10 mils, and the initial transmission does not vary too promiscuously.

All irradiations have been carried out with the cellophane films in separate envelopes sandwiched between ⅛-in.-thick polyethylene sheets. A cobalt-60 γ-ray source of the type described by Henley (*14*) and Manowitz (*15*) was used.

Figure 2 shows the change in per cent transmission vs dose for several different initial film readings. Reduction of the dye by radiation is a random shotgun process; a constant fraction of the dye remaining is continuously reduced to the leuco form, and a first-order reaction is obtained. The correlation has been made in terms of transmission so that the dosage can be expressed as a straight-line function of optical readings. Between 0 and 3×10^5 r, the curves follow the equation

$$T = (1.47 \pm 0.03)10^{-6} r + T_0$$

where T = per cent transmission at a dose r, r = dose in roentgen, and T_0 = initial transmission at $r = 0$.

The probable error varies from about 60% in the 200,000-r range to 7% at 3×10^5 r. Further work will improve the accuracy, dependability, and general utility of these films.

* * *

The samples of cellophane were supplied by du Pont, and support for various phases of this work was furnished by the AEC under Contract AT(30-1)-1186.

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TECHNICAL BRIEFS

• **Electronically controlled** manipulator, incorporating force reflection, has been constructed at Argonne National Laboratory. Developed by R. C. Goertz and W. M. Thompson of the Remote Control Engineering Div., unit's design was reported earlier in NUCLEONICS (Nov. '52, p. 43). Manipulator is used with Argonne's three-dimensional television system for remote operations.

• **"Zipper" scattering chamber,** reported at the June '54 American Physical Society Minneapolis meeting by C. J. Cook, provides continuously variable vacuum port for studying energy and angular spectrum through 0–150 deg symmetrically about the incident beam. Two rubber diaphragms under pressure form vacuum-tight seal along slot in vacuum-chamber wall; port slides between diaphragms without destroying vacuum. Detecting apparatus is placed outside active portion of scattering cell.

• **Exhausted filter cartridges,** containing concentrated waste fission products, are suggested by Atomic Energy Waste Disposal Service, Oakland, Calif., for sterilization of pharmaceuticals and food. These resin-exchange cartridges should provide inexpensive sources.

• **Periscope with depth perception** has been developed at Hanford. First model has magnification variable up to 10×, 15-ft length, 7-in. diameter, and cost $4,500 to build. In this relay stereo microscope two required images are picked up by a single objective lens and transferred through a single set of relay lenses where they are brought to focus before a variable power binocular microscope. Confusion of images is avoided by beaming them at different angles or through different lense areas. It is mechanically simple to build, has no adjustments, and images cannot get out of alignment.

• **Photomultiplier test device,** developed by du Pont Instrument Development Division, checks resolution and relative gain. Device consists of pulsed light source, optical filter, and preamplifier. Photomultiplier output pulses are examined by sweeping pulse-height analyzer. Resolution, computed from graph of pulses per unit time vs pulse height, is easily read to within 0.3%.

• **Co^{60} therapy unit,** used for cancer treatment at Argonne Cancer Research Hospital, utilizes Veeder-Root gasoline pump computer to indicate radiation dosage, exposure time, and dose rate. Cobalt-60 cartridge is in center of 850-lb uranium casting, said to be largest ever made, constructed at Argonne National Laboratory.

• **High-vacuum seal-off valve,** devised by R. J. Richards of NBS, protects vacuum system from atmosphere at all times and may be used as pressure seal or combination safety and seal-off valve. Principal parts are valve handle and stem, valve body and seat, and removable bonnet enclosing seat assembly and adjacent end of stem. Movable seat contains six ports through which system is pumped out. To reduce bulkiness, all parts except seat assembly are removed as unit.

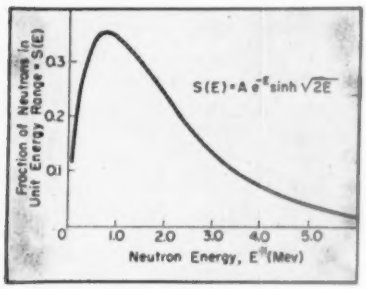

FIG. 1. Energy distribution of fission neutrons from U^{235}

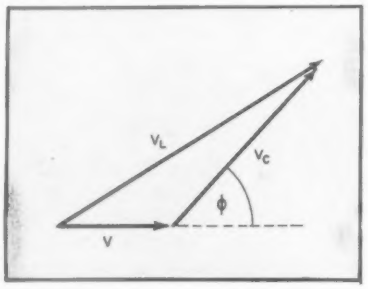

FIG. 2. Relation of velocities in center-of-mass and laboratory systems

How to Use the

Fission-Spectrum Formula in Reactor Calculations

By R. L. MURRAY, M. R. KELLER and D. E. HOSTETLER
North Carolina State College, Raleigh, N. C.

Energy-distribution measurements of U^{235}-fission neutrons accurately fit the semi-empirical formula in Fig. 1 (*1-3*). The relation can be used to determine values of the effective slowing-down length of neutrons in a reactor moderator and to evaluate the average diffusion coefficient of epithermal neutrons for group-diffusion theory (*4*).

This article derives the spectrum formula, presents useful formulas for calculations, and tests an approximate procedure involving replacement of the spectrum by a 2-Mev monoenergetic source.

Fission Spectrum

The spectrum formula is based on the assumption that a neutron escapes from a moving fission fragment with equal probability of motion in all directions, and with an energy distribution function $F(\epsilon)$.

From Fig. 2, it is seen that

$$v_L^2 = v_C^2 + V^2 + 2Vv_C \cos\phi \quad (1)$$

where V = velocity of fission fragment of mass M, E_f = energy of fission fragment, v_C = neutron velocity relative to the fragment (center-of-mass system*), ϵ = energy of neutron relative to the fragment, v_L = neutron velocity as observed (laboratory system).

The range of emission energies $\epsilon = (1/2)mv_C^2$ that will yield a given observed speed v_L is from $\epsilon_{min} = (1/2)m(v_L - V)^2$ at $\phi = 0$ to $\epsilon_{max} = (1/2)m(v_L + V)^2$ at $\phi = \pi$.

First consider the isotropic emission from the fragment of monoenergetic neutrons of energy ϵ. The fraction emerging in the range of angles $d\phi$ at ϕ is $(1/2)\sin\phi\, d\phi$. By differentiation of Eq. 1 this is also equal to $v_L dv_L/(2Vv_C) = dE/(2V\sqrt{2m\epsilon})$. The number of neutrons *emitted* from the fragment in an energy range $d\epsilon$ is taken to be $F(\epsilon)\, d\epsilon$. The number that are *observed* in a range dE is thus the sum of all those that yield the speed v_L or the energy E, i.e.

$$S(E)\, dE = \int_{\epsilon_{min}}^{\epsilon_{max}} F(\epsilon)\, d\epsilon \frac{dE}{2V\sqrt{2m\epsilon}}$$

It is now assumed that the emission distribution is a maxwellian function

$$F(\epsilon) = \frac{2}{\sqrt{\pi Q^3}} \sqrt{\epsilon}\, e^{-\epsilon/Q}$$

where Q is a characteristic energy corresponding to a nuclear temperature, and the function is normalized to one neutron. Thus, the observed distribution is

$$S(E) = \frac{1}{V\sqrt{2\pi mQ}} \int_{\epsilon_{min}}^{\epsilon_{max}} e^{-\epsilon/Q}\, d\epsilon$$

Integration and rearrangement gives

$$S(E) = \frac{2}{V\sqrt{2\pi m}} e^{-mE_f/MQ}\, e^{-E/Q} \sinh \frac{2}{Q}\sqrt{(m/M)E_f}\,\sqrt{E}$$

The choice of $Q = 1$ Mev and $(m/M)E_f = 0.5$ Mev appears to yield the best fit to experimental data; thus the formula reduces to that in Fig. 1. The factor normalizing the distribution to one neutron is $A = \sqrt{2/(\pi e)} = 0.484$.

Average, Most-Probable E

Instead of taking account of the fission-neutron energy distribution, it is often convenient to consider that all neutrons have a common energy equal to the average value

$$E_{avg} = \int_0^\infty E\, S(E)\, dE = A \int_0^\infty E\, e^{-E} \sinh\sqrt{2E}\, dE$$

Replacement of $\sinh\sqrt{2E}$ by its equivalent $(e^{\sqrt{2E}} - e^{-\sqrt{2E}})/2$, and the substitution $\sqrt{E} = x + 1/\sqrt{2}$ in the respective integrals yields

$$E_{avg} = A\sqrt{e}\left[\int_{-1/\sqrt{2}}^{\infty}\left(x+\frac{1}{\sqrt{2}}\right)^3 e^{-x^2}\,dx - \int_{-1/\sqrt{2}}^{\infty}\left(x-\frac{1}{\sqrt{2}}\right)^3 e^{-x^2}\,dx\right]$$

$$= A\sqrt{e}\left[\int_{-1/\sqrt{2}}^{1/\sqrt{2}}(2x^3+3x)e^{-x^2}\,dx + \int_0^\infty\left(\frac{6x^2+1}{\sqrt{2}}\right)e^{-x^2}\,dx\right]$$

The first integral over an odd function between limits symmetric about the origin is zero; the second definite integral is $\sqrt{2\pi}$. Since $A = \sqrt{2/(\pi e)}$, we find $E_{avg} = 2$ Mev. The peak of the distribution occurs at the energy E_p for which the slope of $S(E)$ is zero. It readily can be shown from the resulting condition, $\sqrt{2E_p}\tanh\sqrt{2E_p}$

* Center of mass can be assumed to remain in the fragment because of the low neutron mass relative to that of the heavy nucleus.

$= 1$, that the most probable energy $E_p = 0.720$ Mev.

Slowing-Down Density

The slowing-down density, symbolized by $q(E,\mathbf{r})$ is defined as the number of neutrons crossing an energy level E per unit volume per second at a point $\mathbf{r}$ in a moderator. In a nonabsorbing medium of infinite extent, the number of original fission neutrons that slow down past a given energy E each second is independent of position and is clearly equal to the total number produced each second above that energy, thus

$$q(E) = \int_E^\infty S(E)\,dE \qquad (2)$$

This integral can be evaluated by methods analogous to those in the previous section.

$$q(E) = \frac{A}{2}\left[\int_E^\infty e^{-(E-\sqrt{2E})}\,dE - \int_E^\infty e^{-(E+\sqrt{2E})}\,dE\right]$$

In the first integral, let $x = \sqrt{E} - 1/\sqrt{2}$; in the second, let $x = \sqrt{E} + 1/\sqrt{2}$ and make use of integral tables to obtain

$$q(E) = S(E) + 1 - [\mathrm{erf}(\sqrt{E} + 1/\sqrt{2}) + \mathrm{erf}(\sqrt{E} - 1/\sqrt{2})]/2 \qquad (3)$$

where $\mathrm{erf}(u) = 2/\sqrt{\pi}\int_0^u e^{-y^2}\,dy$, with $\mathrm{erf}(-u) = -\mathrm{erf}(u)$. Note that $q(0) = 1$, which checks the correctness of the normalization factor A. In the limit $E \to \infty$, $q \to 0$, as expected. Figure 3 shows $q(E)$ as computed from Eq. 4 using tables of the error function.

In neutron shielding calculations, the function $q(E)$ can be used as the fraction of fission neutrons emitted with energies larger than a specified value E.

Diffusion Coefficient

The two-group method of determining a reactor's critical size and neutron-flux distribution involves solving the coupled differential equations representing the behavior of two classes of neutrons. These are the thermal group, of characteristic energy E_{th}, and the "fast" group. The latter is a mathematical fiction with properties equal to those of the (properly chosen) average epithermal neutron. The "fast" group is assumed to obey a law of diffusion $\mathbf{j} = -D_1\nabla\phi$ where $\mathbf{j}$ is the neutron current, D_1 is the fast diffusion coefficient and $\nabla\phi$ is the gradient of the

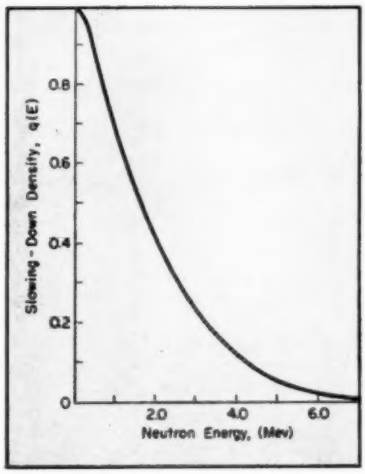

FIG. 3. Slowing-down density of neutrons in infinite nonabsorbing moderator

fast flux. The quantity D_1 is the average of the energy-dependent diffusion coefficient $D = \lambda_t/3$* over the range of energies above thermal, using the appropriate flux as a weighting factor.

$$D_1 = \int_{E_{th}}^\infty D(E)\phi(E)dE \Big/ \int_{E_{th}}^\infty \phi(E)dE \qquad (4)$$

where $\phi(E)$ is the flux density of neutrons at energy E. According to Fermi age theory for an infinite noncapturing medium, the flux is given by

$$\phi(E) = q(E)/\xi\Sigma_s$$

where ξ is the average change in the natural logarithm of the neutron energy per collision with moderator nuclei. The expression for the slowing down density q given in Eq. 3 can be used in conjunction with tabulated cross sections to minimize the numerical integrations in obtaining D_1.

An alternative method of finding D_1 is to assume that all fission neutrons start at the average energy $E_{avg} = 2$ Mev. This implies that q is a constant, equal to the number of fission neutrons emitted per second. As such, q cancels out in the quotient of Eq. 4. Integration of D_1 is then performed with limits E_{th} and 2 Mev. Thus

$$D_1 \simeq \int_{E_{th}}^2 \frac{\lambda_t}{3\xi\Sigma_s}\frac{dE}{E} \Big/ \int_{E_{th}}^2 \frac{1}{\xi\Sigma_s}\frac{dE}{E}$$

Integrations were made using the two methods and tabulated cross sections (5). For a water moderator, D_1 is 1.085 when fission distribution is assumed and 1.020 when a 2-Mev source is used. For a graphite ($\rho = 1.62$) moderator, D_1 is 1.054 for the fission distribution and 1.067 for the 2-Mev source. The agreement is surprisingly good. In view of the uncertainties in rigor of age theory, two-group method, and in cross sections of oxygen and carbon in the high-energy range, estimates based on the assumption of a 2-Mev source are often adequate.

Exploratory estimates on moderators composed of mixtures are facilitated by the simpler method. For such computations, the cross sections are sums over the components, weighted by the volume fractions f. Thus

$$1/\lambda_t = \Sigma_t = f_1\Sigma_{s_1}T_1 + f_2\Sigma_{s_2}T_2 + \ldots$$
$$\xi\Sigma_s = f_1\xi_1\Sigma_{s_1} + f_2\xi_2\Sigma_{s_2} + \ldots$$

Slowing-Down Length

Slowing-down length L_s of fission neutrons from their origin at energy E to the point in space at which they reach thermal energy E_{th} is given by Fermi-age theory as

$$L_s^2 = \tau(E) = \int_{E_{th}}^E \frac{\lambda_t}{3\xi\Sigma_s}\frac{dE}{E}$$

The average age for a fission distribution is then defined as

$$\tau_{avg} = \int_{E_{th}}^\infty \tau(E)S(E)dE$$

Since the product $\xi\Sigma_s$ is a function of energy, numerical integration is required for both stages of the calculation.

An approximate value derived by assuming fission energy of 2 Mev is

$$\tau_{avg} \simeq \int_{E_{th}}^2 \frac{\lambda_t}{3\xi\Sigma_s}\frac{dE}{E}$$

The two formulas were tested for graphite, to which age theory is applicable. The values of τ_{avg} (in cm^2) were 342.7 for fission distribution, 349.2 for the 2-Mev source, and 350 experimentally. As was found in the calculation of D_1, the approximation using 2 Mev is accurate for the pure substance and simplifies computations for mixtures.

* Transport mean-free-path λ_t is given by $1/(\Sigma_s T)$, where Σ_s is the macroscopic scattering cross section and $T = 1 - 2/(3M)$, M is the mass ratio of nucleus and neutron.

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THE COVER—Same Goal for All Reactor Types: Competitive Nuclear Power

Advances along the various routes toward economically competitive nuclear power are illustrated on the cover. From basic types (represented by blocks at bottom), new systems have evolved.

Organizations and the reactor types they are developing include: Argonne National Laboratory, breeders and boiling-water reactors; Oak Ridge National Laboratory, homogeneous reactors; Los Alamos National Laboratory, water boilers; North American Aviation, water boilers and sodium-graphite reactors; Westinghouse Atomic Power Division, pressurized-water reactors and submarine thermal reactors; Knolls Atomic Power Laboratory, submarine intermediate reactors.

AEC's new 5-yr power-reactor development program (NU, May '54, p. 72; July '54, p. 48) is aimed at getting the facts necessary to develop the most economically-promising cycles (NU, June '54, p. 13).

Symbol designations, names, and locations of the various reactors are given here. Brief technical descriptions of many of these reactors have been published previously (NU, March '52, p. 10; June '53, p. 65).

Homogeneous Reactors

LOPO, Low-Output Pile; Los Alamos, N. M.
HYPO, High-Output Pile; Los Alamos, N. M.
SUPO, Super-Output Pile; Los Alamos, N. M.
HRE-1, Homogeneous Reactor Experiment No. 1; Oak Ridge, Tenn.
NAA, North American Aviation's Water Boilers; Downey and Livermore, Calif.
RALEIGH, North Carolina State College Water Boiler; Raleigh, N. C.
HRE-2, Homogeneous Reactor Experiment No. 2; Oak Ridge, Tenn.
HTR, Homogeneous Thorium Reactor; Oak Ridge, Tenn.

Liquid-Metal Reactors

LOS ALAMOS FAST Reactor (plutonium fuel); Los Alamos, N. M.
EBR-1, Experimental Breeder Reactor No. 1; Arco, Idaho
EBR-2, Experimental Breeder Reactor No. 2; Arco, Idaho
SIR-A, Submarine Intermediate Reactor; (land-based) West Milton, N. Y.
SIR-B, Submarine Intermediate Reactor; U. S. S. Sea Wolf

Sodium-Graphite Reactor

SRE, Sodium Reactor Experiment; Santa Susana, Calif.

Graphite Piles

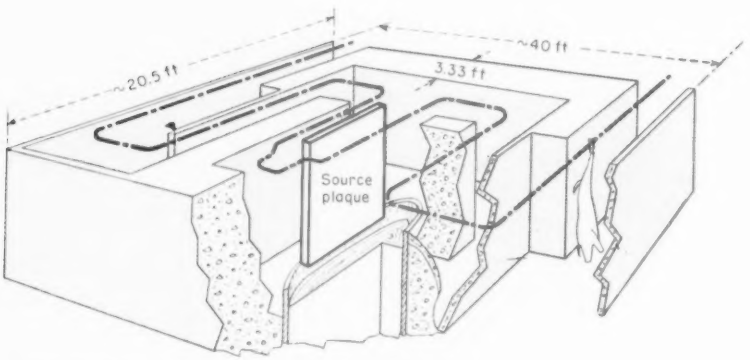
CP-1, Chicago Pile No. 1; Lemont, Ill.
CP-2, Chicago Pile No. 2; Lemont, Ill.
X-10, Oak Ridge Graphite Pile; Oak Ridge, Tenn.
HANFORD, Hanford Plutonium-Production Reactors; Richland, Wash.
BNL, Brookhaven National Laboratory Reactor; Upton, N. Y.

Light-Water Reactors

MTR, Materials Testing Reactor; Arco, Idaho
STR-1, Submarine Thermal Reactor (land-based prototype); Arco, Idaho
STR-2, Submarine Thermal Reactor; U. S. S. Nautilus
PWR, Pressurized-Water Reactor; Shippingport, Pa.
BOILING EXPERIMENTS, Arco, Idaho
EBWR, Experimental Boiling Water Reactor; Arco, Idaho

Heavy-Water Reactors

CP-3, Chicago Pile No. 3; Lemont, Ill.
NRX, National Research Experimental Reactor; Chalk River, Ont., Canada
CP-3′, improved CP-3; Lemont, Ill.
CP-5, Chicago Pile No. 5; Lemont, Ill.
SAVANNAH, Savannah River Production Reactors; Aiken, S. C.



For this type facility, estimates have been made of the . . .

. . . Economics of Pork Irradiation

By H. J. GOMBERG, S. E. GOULD, J. V. NEHEMIAS, and L. E. BROWNELL
University of Michigan
Ann Arbor, Michigan

Radiation is a well-established tool for breaking the trichinosis cycle in pork (*1*). But its economic feasibility has been an unresolved problem. This article presents a *cost* study of a meat-processing plant designed to use radiation from cesium-137 to irradiate hog carcasses.

The plant shown in the figure is designed to irradiate 2,000 carcasses in the 24–48-hr normal delay period between carcass preparation and cutting. For access to the chill room, the irradiation unit is on the second floor.

The irradiation source is a large plaque. It provides a broad uniform radiation field through which the carcass passes suspended from an overhead conveyor.

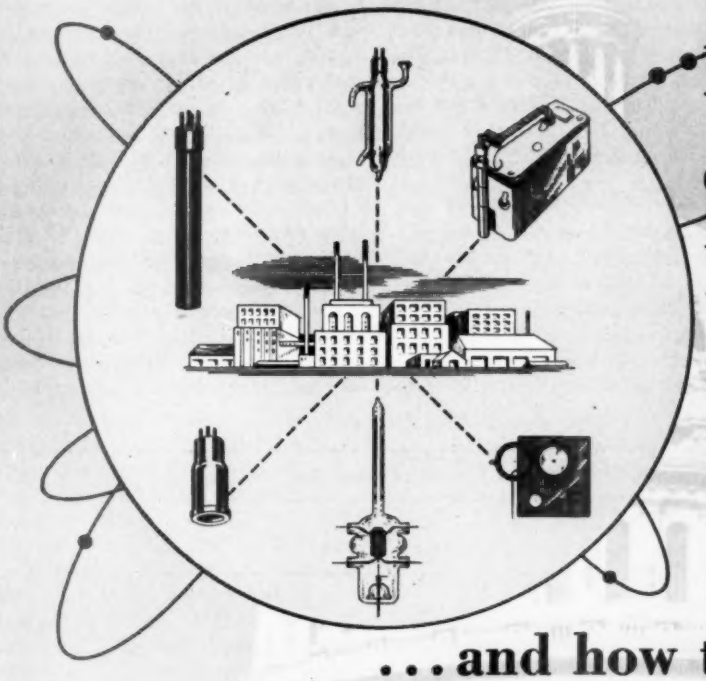
Gamma Source

In selecting a source of gamma radiation for this design, mixed fission products* of various ages were considered and compared with Cs^{137}. In general, the mixed fission products have the advantage of being available in much larger quantities than Cs^{137}. However, on bases of economics, radiation emitted and its absorption characteristics, Cs^{137} has numerous advantages over mixed fission products.

During maintenance work in the irradiation chamber the source plaque is stored under water in the well. The

* "Mixed" fission products are the combination of radioactive elements remaining after unused uranium is removed from spent reactor fuel.

The NEW and IMPORTANT ROLE of INDUSTRY in the Field of NUCLEONICS



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plaque is raised into the chamber for pork irradiation. Using a single plaque 6 ft long by 5 ft by 0.4 in., 2,000 hogs can be irradiated each day by bringing the hogs on a conveyor past both sides of the plaque. The radiation intensity at 21 in. (corrected for absorption) is about 13,500 r/min. With a 1.5-Mc source the pork surfaces accumulates 30,000 r in 2.1 min when it is conveyed at a speed of 6.67 ft/min. The center of a 14-in.-thick carcass receives 25,000 r. A dose of 15,000 r sterilizes trichina so that they cannot reproduce and cause infection.

Cost of Radiation Chamber

Total initial investment for the radiation chamber will be about $566,000. Of this, $58,000 is for construction of the chamber [without source and accessories, the $45/yd^3 cost compares favorably with the $42–50/yd^3 range for industrial buildings (*2*)]. The stainless-steel well (16 ga × 9 ft × 4.5 ft × 24 ft) will cost $2,500; excavation for footings and shorings, $600; 375 yd^3 of concrete for walls, flooring, and roof will run to $7,500 (labor, forms, and reinforcing will cost an additional $8,250). A sum of $600 will be required to rent a crane to raise concrete to the second floor. Other construction items are: elevator mechanism, $2,500; ion exchange equipment for well water, $3,000; monitoring equipment, $4,000; wiring, $200; water lines and pipefitting labor, $800; access doors with safety interlock, $1,200; ventilation system, $2,000; refrigeration lines, $4,000; backgrading and painting, $450; conveyor mechanism, $6,400; and engineering, contractor and miscellaneous fees will run to $14,000.

A shipping container for Cs^{137} sources might be supplied by AEC or by an industrial handler of fission-product sources. If not, a steel-reinforced lead

Annual Operating Costs of Pork-Irradiation Unit

Item	*Cost ($/yr)*
Wages, salaries	
Experienced health physicist (½ time)	4,000
Maintenance engineer with health physics training (½ time)	3,000
Cleaning and sanitation (part time)	1,000
	8,000
Supervision and clerical labor (10% of operational labor)	800
Salaries and wages not associated with operation of radiation chamber (50% of direct labor and supervisory costs)	4,400
	13,200
Other operating costs	
Maintaining source activity	25,000
Refrigeration	2,000
Utilities	1,000
Conveying	1,000
Repairs and maintenance of radiation chamber (5% of chamber's cost)	2,900
Misc. (ion exchange resin, and misc. contingencies)	1,500
	33,400
Overhead	
Payroll overhead (15% of cost of direct labor and supervision)	1,980
General plant overhead (50% of cost of labor and operation)	23,300
General administration overhead (10% of cost of labor and operation)	4,660
	29,940
Taxes, interest, insurance	
Property taxes (2% cost of radiation chamber)	1,160
Income tax (2½% of total investment)	14,150
Interest (5% of total investment)	28,300
Insurance (1% of total investment)	5,660
	49,270
Depreciation, obsolesence	
Radiation facility: (58,000 × 0.08)	4,630
Radiation source: (initial cost − salvage value) × (8%) = (483,000 − 241,500) × (0.08)	19,260
	23,890
TOTAL	149,700

container approximately 2 ft × 7 ft × 8 ft would cost about $25,000, would weigh about 50 tons and could be shipped on a flat car.

Although insufficient information is available to estimate the source cost reliably, three approaches indicate that $483,000 is a reasonable figure.

Kilocurie Cs^{137} gamma sources processed from fission products can be supplied by the Atomic Energy Commission for $5,000. Installation costs (not including the shipping container) would total about $1,000 for a plant in the Michigan area. Thus, $6,000 is a reasonable installed cost for 1 kc of Cs^{137}. Using the 0.6-power factor (*3*) for scaling up to a 1.5-Mc source, the installed cost is estimated to be: $6,000 $(1.5 \times 10^6/10^3)^{0.6} = \$483{,}000$.

Another approach to cost estimation can be made on the basis of prices for Cs^{137} teletherapy sources, which are now $100 for the first curie and $25/c for additional activity. Using the same scaling-factor approach for transition from small- to large-scale operation and using a base price of $100/c, the cost of 1.5 Mc would be $507,600. On the same conditions, with a $50/c base the total cost would be $253,800; and for a $25/c base the total would be only $126,900. A third approach estimates that modern large-scale techniques could separate Cs^{137} in megacurie amounts for about $0.30/c (*4*). A 1.5-Mc source would cost $450,000. The range of values from these varied approaches indicates that $483,000 is a reasonable estimate.

Operating Costs

Annual operating costs are shown in the table. In estimating operating costs other than wages and salaries, an allowance is made for charging a portion of the cost of refrigerating and conveying the pork.

Source strength drops 10% every 5 yr. The cost of restoring this is calculated to be $125,000 every 5 yr. Straight-line amortization would make 20% chargeable each year. Overhead on the payroll, general plant operation, and general administration is estimated according to recommended methods for chemical plants (*3*).

The radiation chamber is considered taxable as property, but the radiation source is a piece of equipment and not subject to property tax. Income tax should be calculated on the basis of profits or estimated as a percentage of annual sales; however, the plant is not designed on a profit basis. Therefore,

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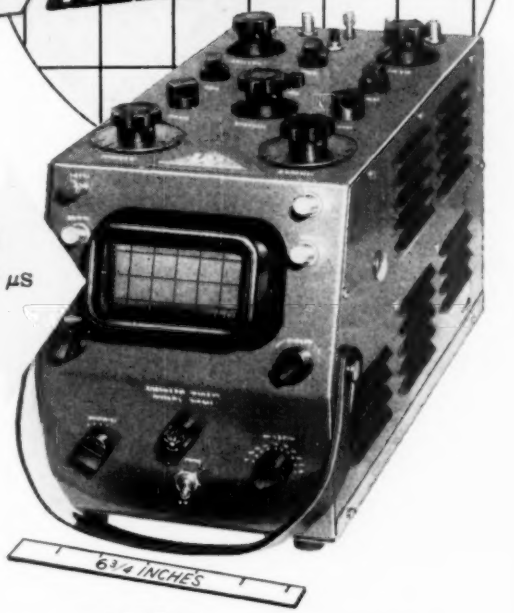

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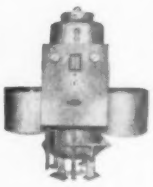

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2½% of the total investment is used as an estimate of income tax considered chargeable to the irradiation facilities.

In estimating depreciation and obsolescence, the radiation chamber and radiation source are considered to have a 10-yr useful life. The total investment is amortized in a 10-yr period by use of a sinking fund. The interest on the cash paid into the sinking fund reduces the percentage of the initial investment chargeable each year from 10% to about 8%. This depreciation would provide for complete replacement of the chamber after 10 yr. The source is assumed to have only 50% salvage value at the end of the 10-yr amortization period even though, through activity replacement, it will be at full strength.

Based on production figures for 1950, 68,504,000 head of hogs yielded 9.265-million lb of pork. Thus the average hog yields 135 lb of pork, excluding lard. Basing the design on a rate of 2,000 hogs/day and operation 260 days/year, plant production is 70,200,000 lb/yr. Thus the operating cost to be added to the price of pork is 2.1 mills/lb, or $0.29/hog.

The large investment required for the radiation source might discourage adoption of special processes employing radiation. Rapid strides made by industry in developing new techniques necessitates amortization of new processes over a short period. However, because long-lived radiation sources maintain their value independent of the process in which they are employed, they should be rented either by AEC or by a contractor rather than sold. This would permit amortization realistic with the actual useful life of the source. Rental of a source such as used in this design might be as low as $25,650/yr (*5*). This could make processing by radiation much more attractive to industry.

* * *

This article is based on a paper presented at the American Institute of Chemical Engineers' International Congress on Nuclear Engineering, Ann Arbor, Michigan, June 25, 1954.

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2. O. T. Zimmerman, I. Lavine, *Ind. Res. Serv.* (1950)
3. C. H. Chilton, *Chem. Eng.* **57**, No. 4, 112 (1950)
4. Harold Ohlgren, formerly chief engineer of Chemical Processing Plant, National Reactor Testing Station, private communication
5. L. E. Brownell, ed., COO-198, p. 165 (1954)

Nuclear Constants in Reactor Design

By HANS A. BETHE
Cornell University
Ithaca, N. Y.

Reactors differ in neutron spectrum, neutron economy, initial cost, cost of generating power, and degree to which they produce or consume fissionable materials. A large-scale nuclear power economy can be built up and sustained only if an appreciable fraction are of the breeder type. This will be particularly true in the beginning of nuclear-power development and in the face of continuing military demands.

Progress has made it possible to pay more attention to such engineering features as ease of heat extraction, value of steam produced, ease of control, ruggedness and so on. However, funda-

Cross Sections in Barns*

	Element						
Property	*H*	*C*	*Na*	*Fe*	*Ag*	*Au*	*Pb*
Atomic weight	1	12	23	56	108	197	207
Fast	(>1 Mev)						
Scattering	4.5	3	3	3	6	6	6
Inelastic	0	0	0.3	1	1.5	2	0.5
Capture	5×10^{-5}	10^{-3}?	0.0014	0.005	0.17	0.14	0.002
Thermal	(1/40 ev)						
Scattering	20	5	3.5	11	6.6	7	11
Capture	0.3	0.005	0.6	2.4	80	96	0.2

* 1 barn = 10^{-24} cm²/nucleus

mental nuclear properties summarized in the table must not be neglected.

Fission cross sections for fast neutrons are of the order of one barn, for slow neutrons in U^{235} about 500 barns. In a fast reactor, a large fraction of the neutrons suffer inelastic scattering even if the amount of nonfissionable material is kept to a minimum. Thus, the neutrons are degraded to a few hundred kev. Further degradation takes place very slowly if light materials are not present.

In fast-breeder reactors, a high neutron energy is desired. Thus, the amount of structural material and coolant is held to a minimum. Consequently, fast reactors are small in size. On the other hand, to obtain a thermal reactor, large amounts of materials of low atomic weight (such as water, graphite or beryllium) are employed. These reactors are generally larger than fast reactors, but they become really large only when natural or slightly-enriched uranium is used as fuel.

Neutron capture must be avoided as far as possible. The effect of a given element A in this respect is given by (number of atoms of A times capture cross section of A/number of atoms of U^{235} times fission cross section of U^{235}).

The ratio of the number of atoms is usually less favorable for thermal-neutron reactors because these are larger in size and therefore contain more foreign atoms per unit of U^{235}. The ratio of cross sections is about the same for thermal and for fast neutrons for most of the elements listed in the table. Because of the atomic ratio, the neutron capture is usually more serious in thermal reactors than in fast ones.

Heavy elements generally absorb much more readily than light ones and must, therefore, be carefully avoided. Notable exceptions are lead, bismuth and to a lesser extent zirconium and barium, all of which have small absorption. This would make lead and bismuth available as coolants, at least from the neutron point of view. Another important exception is U^{238}, which has a thermal capture cross section of less than 3 while the capture cross section for faster neutrons is similar to that of gold and other heavy elements. Thus, when using natural uranium the neutron economy is greatly improved by slowing the neutrons down to thermal energy.

The smaller sensitivity of fast reactors to capture makes possible a wider choice of materials for these reactors. This partially offsets the great diffi-

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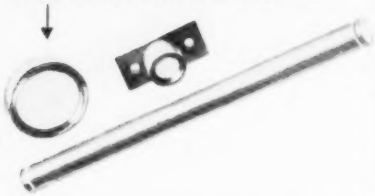
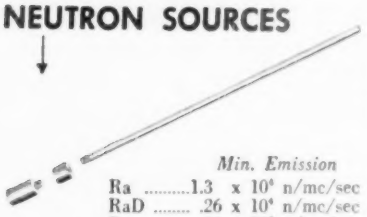


Beta Gauge.....Ra, RaD, Sr^{90}, Tl^{204}
Liquid Level Gauge.....Cs^{137}, Ru^{106}, Co^{60}
Standards.....Alpha, Beta, Gamma

NEUTRON SOURCES



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Po	.26 x 10^4 n/mc/sec

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culty of extracting the heat from a small reactor.

Reactors using an enriched fuel use only a fraction of the fission neutrons to generate new fissions. The critical size can be substantially reduced by a good reflector. With few exceptions, the scattering cross sections of various elements do not differ greatly, so that the main consideration for a good reflector is the number of atoms per unit volume.

In a fast reactor, it is usually desirable that the reflector not degrade neutrons too much; elements of atomic weights from 20 to 40 are usually most suitable because they have little inelastic scattering and not too much energy is lost in elastic scattering. On the other hand, for thermal reactors, a reflector made of light atoms is desirable, and heavy atoms (weight 100 or more) must be carefully avoided because of their absorbing properties.

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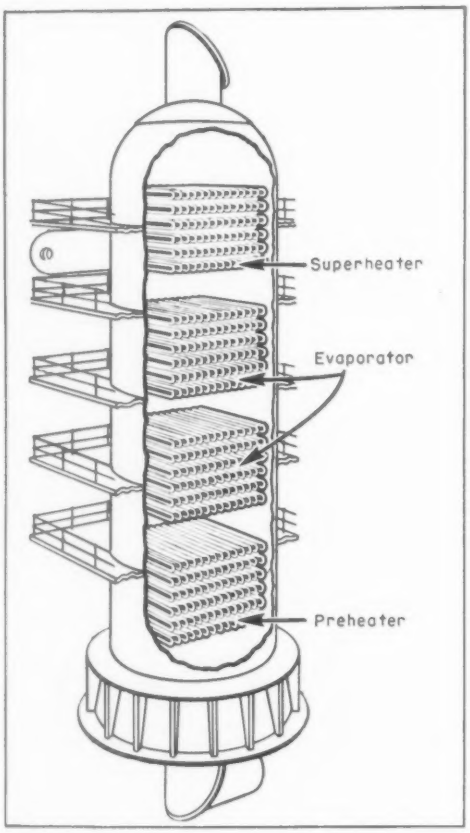
• **East Germans** plan to build two reactors that will consume 26,400 lb of uranium per year. To be built near Aue, Saxony, the installation will be a supranational Red-bloc project.

• **Ceramic coatings** with low thermal neutron absorption cross sections (0.15–0.50 barns) have been developed by the National Bureau of Standards. When used as 1-mil coatings for various structural alloys, they reduce metallic corrosion at temperatures up to 1,800° F.

None of the coatings so far tested greatly reduces depth of uniform oxidation of the metal, but they markedly decrease number, depth, and cross-sectional area of stringer penetration (random corrosion along grain boundaries, usually four to twenty times deeper than surface oxidation).

Five coatings gave appreciable protection to type 321 stainless, ten protected 309 stainless, fourteen performed well with 310 stainless. All worked well on Inconel and other alloys with low coefficients of expansion. The coatings are boron-free and combine a high barium frit with a ceric or ceric-chromic oxide refractory.



HEAT FROM BRITAIN'S first power reactors at Calder Hall will generate steam in eight 80-ft-high steel towers similar to the one shown (NU, Feb. '54, p. 74). Four towers will be located outside each of the two reactor buildings. Pressurized CO_2 coolant from reactors will circulate outside the preheater, evaporator, and superheater coils to convert water inside tubes to superheated steam. Heating surfaces are of flash-welded stud-tube construction. A double-pressure steam cycle will be used. Each tower will have a separate high- and low-pressure section, each section with its own drum, feed pump, economizer, evaporator, and superheater sections. Firms working on the Calder Hall power station include: Babcock & Wilcox (entirely separate from its U. S. namesake), towers; Whessoe Ltd., reactors' pressure vessels; C. A. Parsons & Co., Ltd., blowers and pipework; Taylor Woodrow, buildings

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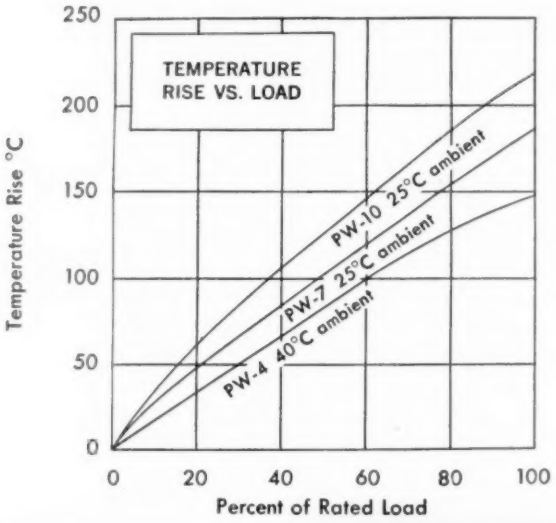

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BOOKS

Nuclear Physics

By W. HEISENBERG (Philosophical Library, New York, 1953, ix + 225 pages, $4.75). Reviewed by PETER G. BERGMANN, Syracuse University, Syracuse, New York.

This slim volume represents the translation of the German original, whose last revised edition had appeared in 1948 and which was based on a series of lectures that Heisenberg delivered at the request of the German Society of Electrical Engineers. It is addressed, not to fellow nuclear physicists nor even to fellow physicists, but to "readers who, while interested in natural sciences, have no previous training in theoretical physics and yet are familiar to a certain extent with physical ideas." This English edition also contains an appendix on German attempts to develop nuclear power during the Second World War, which had appeared previously in *Nature* in 1947.

The book begins with a historical introduction that sketches the fate of the notion of atomic constitution of matter from classical antiquity up to the end of the nineteenth century. It goes on to a more detailed exposition of the Rutherford atomic model, the structure of molecules, and the periodic table of elements. Penetrating more deeply into the atomic nucleus proper, Heisenberg devotes the third chapter to natural and artificial radioactivity and the building blocks of nuclei. The following three chapters are devoted to a detailed discussion of the binding energy of nuclei, the nature of nuclear forces proper and the contribution of Coulomb forces to the structure and stability of nuclei, and the nuclear reactions, including fission. Chapter 7 is devoted to nuclear instrumentation, and the eighth and last chapter to applications, i.e., the construction of nuclear reactors, the use of unstable isotopes as tracers in chemistry, biology, biochemistry, and medicine, and the uses of stable isotopes. The appendix, on German nuclear engineering, has already been mentioned. There are the usual tables, a very brief bibliography, and an index.

The book is well organized and written in a fluid style, though this reviewer found the original German of Heisenberg considerably more elegant than the English of the (anonymous) translator. As pointed out in the preface by Heisenberg himself, the development in nuclear physics since the end of the war has continued at such a rapid pace that a book that was last revised six years ago is already quite out of date. There could not have been any treatment of the nuclear shell model; there is no discussion of recent experiments on the existence of the neutrino. The only mesons discussed are muons and pions.

This book will be of interest primarily for the interested layman who wishes to study a general introduction to the subject of nuclear physics by a writer of recognized authority, which covers all the important facts known by the end of the Second World War and a few years beyond. It is to be hoped that a further revision will bring the work up to date. A person who has to do with nucleonics professionally will find that the presentation does not go far enough to help him with his everyday problems. But even the expert who is not a physicist may find such a general survey of the field useful in enabling him to see the most recent theoretical and experimental advances in their proper context.

BOOKS RECEIVED

Isotopic Tracers, by G. E. Francis, W. Mulligan, and A. Wormall, John de Groff, Inc., New York, 1954, xvi + 306 pages, $7.00. (*To be reviewed.*)

Millimicrosecond Pulse Techniques, by Ian D. Lewis and Frank H. Wells, McGraw-Hill Book Co., Inc., New York, 1954, xiv + 310 pages, $7.50. (*To be reviewed.*)

Physical Properties of Solid Materials, by C. Zwikker, Interscience Publishers, Inc., New York, 1954, viii + 300 pages, $8.75. (*To be reviewed.*)

Manual for Plastic Welding, Vol. 2, Polyethylene, by G. Haim and J. A. Naumann, The Industrial Book Co., Cleveland, 1954, xii + 128 pages, $6.00. This manual discusses gas-welding technique for polyethylene. Written as a practical welding guide, it covers workshop layout, pipe lines, and lining tanks.

The Man in the Thick Lead Suit, by Daniel Lang, Oxford University Press, New York, 1954, xi + 207 pages, $3.50. With an introduction by Eric Sevareid, this book is a collection of articles originally published in "The New Yorker" magazine. Among them are interviews with Wernher von Braun, Samuel A. Goudsmit, and William G. Pollard; reports of an atom bomb detonation, civil defense planning, and uranium prospecting; and descriptions of Oak Ridge, the Savannah River plant, and the flying-saucer phenomenon.

Guide for Safety in the Chemical Laboratory, Manufacturing Chemists' Association, Inc., D. Van Nostrand Co., Inc., New York, 1954, xiii + 234 pages, $4.25. Safety procedures described in this book include a chapter on *Radiation Safety and Contamination Control in the Laboratory.* Other topics are handling chemicals, protective equipment and devices, contamination, and specific first aid instructions, toxicity, and packaging and transporting chemicals.

ALSO OF NOTE

Nuclear Reactor Development. This report is the proceedings of a forum held under the auspices of Atomic Industrial Forum, Inc., in Washington, D. C., May 24, 1954. Papers and discussions are on the AEC 5-yr reactor development program (Gordon Dean, chairman, L. R. Hafstad, Chauncey Starr, C. H. Weaver, A. M. Weinberg, and W. H. Zinn); private reactor development (Manson Benedict, chairman, C. R. Barthelemy, A. P. Donnell, T. G. LeClair, F. K. McCune, and P. N. Powers); public policy in atomic energy (W. S. Cole, introduced by L. L. Strauss). *Atomic Industrial Forum, Inc., 260 Madison Ave., New York 16, N. Y., $5.00.*

Rotational States of Atomic Nuclei. Aage Bohr surveys nuclear-rotational-state theory and experimental evidence concerning this type of nuclear excitation. The major sections are: *Introduction, Nuclear Deformations, The Collective Rotational Motion, The Rotational Energy Spectrum, and Electromagnetic Moments and Transitions. Ejnar Munksgaard, 6 Norregade, Copenhagen, Denmark, $1.45.*

Vacuum-tube characteristic curves. Pads of 20 identical sheets, $8\frac{1}{2} \times 11$ in., show plate characteristics, positive-grid characteristics, u, g_m, and r_p, plus screen characteristics for pentodes. Reverse side gives electrical and mechanical data and ratings. Tube types available are 12AU7, 12AX7, 12AT7, 6SL7, 6SN7, 6L6

pentode, 6L6 triode, 6AQ5 triode, 5965, 5687, 5751, and 5718. *Technical Publishing House, 15-B Everett St., Cambridge 38, Mass. (1–99 pads, $0.89; 100–499, $0.79; 500 or more, $0.69).*

The Contribution of Atomic Energy to Medicine. This report presents the hearings before the Subcommittee on Research and Development of the Joint Congressional Committee on Atomic Energy, June 2–4, 1954. Phases of the field discussed were: history of atomic energy program in medical research; teletherapy and cancer treatment; biosynthesis of labeled drugs; tracer techniques; calcium-45 arthritis and cancer research; carbon-14 studies of circulatory disorders; carbon-14 steroid research; and use of radioisotopes and synthetically labeled compounds. *Joint Congressional Committee on Atomic Energy, Washington, D. C.*

Corrosion: A Bibliography of Unclassified Report Literature (TID-3048). This annotated bibliography contains 214 references citing corrosion data found in unclassified reports held by the Technical Information Service as of January 1, 1954. Author, subject, and report number indexes are included. *Office of Technical Services, Department of Commerce, Washington 25, D. C., $0.55.*

Hydraulic Research in the United States, 1954. This 193-page NBS publication (publication 210), edited by H. K. Middleton, reports private, university, and government-supported projects by title and number, including sponsor, correspondent, brief description, present status, results and publications. *Government Printing Office, Washington 25, D. C., $1.25.*

Statistical Theory of Extreme Values and Some Practical Applications. This monograph of the NBS Applied Mathematics Series is based on four lectures given at the Bureau of Standards by E. J. Gumbel. Lecture subjects are: exceedances, return periods, and probability. *Superintendent of Documents, U. S. Government Printing Office, Washington 25, D. C., $0.40.*

Optical Image Evaluation (NBS Circular 526). This 289-page publication reports proceedings of the Oct. '51 National Bureau of Standards symposium. The papers and discussion reexamine the older methods of image evaluation as well as newer procedures to place image evaluation on a sounder engineering basis. *Government Printing Office, Washington 25, D. C., $2.25.*

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LETTERS

Radiations' Relative Merits

DEAR SIR:

I should like to offer some comments on "Relative Merits of Cathode Rays and Gamma Radiations," by Goldblith and Proctor (NU, Feb. '54, p. 32). This article presents, I feel, a somewhat distorted comparison of the "relative merits" of these two types of ionizing radiation, and it is only fair that erroneous impressions which may be created be corrected.

It may well be that space limitations made the elimination of all supporting calculations necessary. Nevertheless, in this type of presentation it is essential that the basis for comparisons be completely consistent. Therefore, the assumptions made and the precise methods of computation employed must be clearly stated, for these are the meat of the values offered.

Specifically, I find it necessary to take issue with the following items:

1. "With cathode rays one might expect an efficiency of utilization of energy coming out of the tube of the order of magnitude of 75%."

This statement omits the cardinal point that, assuming 100% efficient absorption of radiation, 75% over-all efficiency is the *maximum* attainable because of the nature of the cathode-ray depth-dose curves. The actual efficiency must, in any case, be *less* than 75% and could, under any specific operating conditions, well be a very small fraction of this value.

2. "Vitro Corp. has calculated that efficiencies of utilization of gamma radiation are much lower; about 14.7% for solid-cylinder absorbers and 31.8% for hollow cylinder sources."

I seriously question whether this efficiency is not about the same as electron-beam efficiency. The value presented is largely a matter of the assumed geometry and other unspecified factors. Duffey,* for example, has clearly pointed out that these utilization efficiencies are not necessarily for optimum design, but rather are simply examples of relative utilization for different assumed geometries.

3. "Calculations made by us indicate efficiency as low as 4% (for fission products)."

* D. Duffey, NUCLEONICS **11**, No. 10, 8 (1953).

No basis for this calculation is given; the authors could presumably have just as well assumed conditions leading to a 0.004% or a 40% efficiency.

4. *"Some rough preliminary calculations have been made of the variations in distribution of ionizing density. . . . The results of these calculations are shown in Figs. 4 and 5."*

Again, no discussion of how these figures were obtained is presented. Figure 4 bears a great similarity to the data of Henley† and Figure 5 to that of Tarpley, Manowitz *et al.*‡ If these were the sources of the original data used, they should have been acknowledged; if not, it might be suggested that these references are where the data *should* have been taken from, since they give experimental data for these specific geometries.

—Ernest J. Henley
Associate, Department of Chemical Engineering
Columbia University
New York, New York

More About PM Sockets

Dear Sir:

In reading Mr. Donald Morken's letter to the editor regarding availability of duodecal sockets (NU, July '54, p. 82), I noted his reference to Du Mont's photomultipliers. The tubes referred to are Du Mont's type 6291, a 1 1/2-in. diameter 10-stage multiplier, and type 6467, a 1 1/4-in. tube also incorporating 10 stages.

At the time these tubes were placed on the market, it was realized that users would require base sockets exhibiting exceptional dielectric properties. As a reference for engineers requiring highly dielectric duodecal sockets, I am furnishing part numbers and descriptions for two such sockets:

Du Mont part 34003960 covers a low-loss phenolic duodecal socket equipped with silver-plated phosphor-bronze contacts.

Du Mont part 34003620 covers a mica-filled duodecal socket equipped with silver-plated beryllium-copper contacts.

Either socket will fit both of the aforementioned multipliers.

—R. H. Arp
Parts Sales and Service Manager
Allen B. Du Mont Laboratories, Inc.
Clifton, New Jersey

† E. J. Henley, Nucleonics **11**, No. 10, 41 (1953).

‡ W. Tarpley, Y. Yudis, B. Manowitz, R. Horrigan, J. Weiss, BNL communication (August, 1952).

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Thickness Inches	Nominal Size
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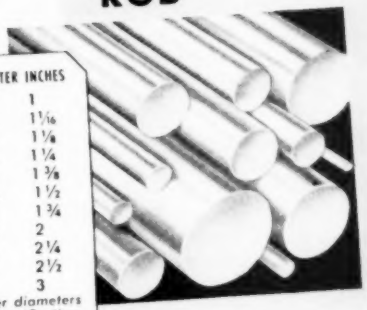
3/32	18 x 18
1/8	24 x 24
3/16	36 x 36*
1/4	48 x 48*
3/8	
1/2 & Up	

* Can be furnished in 1/2 sheets

ROD



DIAMETER INCHES	
1/4	1
5/16	1 1/16
3/8	1 1/8
7/16	1 1/4
1/2	1 3/8
9/16	1 1/2
5/8	1 3/4
3/4	2
7/8	2 1/4
	2 1/2
	3

Other diameters on specification

TUBING

TYPICAL SIZES INCHES	
O. D.	I. D.
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1/2	3/8
3/4	1/2
1	3/4
1 1/2	1
2 1/2	1 1/2
3	1 3/4

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NEWS

President Signs Atomic Energy Law of 1954; Opens Power Field to Industry but Restricts Patents

President Eisenhower signed the Atomic Energy Act of 1954 on August 30 after Congress spent a total of 75 minutes approving the second compromise of House and Senate versions offered by conference committee. Public-power advocates in the Senate had defeated a first attempt at compromise that did not give preference in licensing nuclear power plants to public and cooperative power groups; the final version incorporates such preference. It also requires compulsory licensing of basic patents until September, 1959, thus reverting to the legislation first proposed by the Joint Congressional Committee on Atomic Energy (NU, Aug. '54, p. 57).

W. Sterling Cole, chairman of the Joint Committee, announced that he would reopen the patent question in the next session of Congress on the basis that compulsory licensing is unconstitutional. The new law provides for "reasonable" royalty fees for owners of original patents on inventions of "primary importance," but AEC and any qualified person can obtain a license.

Patents on inventions or discoveries made under contract or other arrangement with AEC are government property unless AEC waives its claim or has its claim invalidated by the Board of Patent Interferences.

Preference to public bodies and cooperatives is granted in two sections of the law. In issuing licenses for a utilization or production facility for generating commercial power, AEC must give such preferred consideration. But primary preference, in cases of limited licensing opportunities, goes in any event to facilities for high-cost power areas.

AEC is also required to give preference in selling power produced by its production or experimental facilities. The key words are, "In contracting for the disposal of such [electrical] energy the Commission shall give priority to public bodies and cooperatives or to privately owned utilities providing electric utility services to high cost areas not being served by public bodies or cooperatives . . ."

Joint Committee lawyers argue that this would have no effect on arrangements between Duquesne Light Co. and AEC on the PWR project (NU, April '54, p. 78). First, they say Duquesne is purchasing heat energy (steam) rather than electric energy. Second, they say no public body or cooperative would want the power because its cost is so high.

Other sections of the new law also included compromises worked out by the conference committee. These:

Provide for a division or divisions within AEC concerned primarily with "application of civilian uses."

Require AEC to notify possible distributors of electricity within transmission distance of an area in which a proposed plant will be located before granting a license.

Make licensees transmitting or mar-

Human Feeding Studies of Irradiated Food to Start; Army Tests Will Hasten Commercial Application

Tests that promise a rapid advance towards commercial application of radiation processing of foods start in January at Fitzsimons Army Hospital in Denver, Colo. The Army is putting twelve volunteers on a diet of irradiated food for over a year to study nutritional adequacy and to prove that this food will have no harmful effects on the human body.

Success of these tests will play a large part in Army adoption of radiation processing of at least part of its food supplies. Equally important, Food and Drug Administration requirements for animal and human testing of irradiated foods prior to public distribution may also be met (NU, Jan. '54, p. 52).

In the current test, only meat products in the diet are being irradiated, but vegetables and liquids will be included after further preliminary work. Foods are irradiated in sealed containers at the Atomic Energy Commission's reactor testing station in Idaho, packed with dry ice for shipment to Denver, and eaten within three days. Used fuel slugs from the Materials Testing Reactor will provide 10^6–10^7 r/hr for irradiation. Total doses will vary from $\frac{1}{2}$- to $2\frac{1}{2}$-million rep, depending on the dosage required for sterilization or pasteurization of the food treated.

Tests will continue for more than a year to obtain significant data. No studies involving storage of the food are contemplated in conjunction with the human feeding program; immediate consumption eliminates this variable from the test. But as the program develops, the effects of storage on toxicity and nutritional degradation will have to be investigated.

The Fitzsimons nutrition laboratory has carried out animal feeding programs since last March in preparation for the human feeding program. No ill effects have been detected in rats.

The human feeding test, supervised by the Office of the Surgeon General, is sponsored by Quartermaster Food and Container Institute, Chicago, Ill. Quartermaster Corps combined its radiation processing studies with AEC's recently, and is planning to spend $6-million on a 5-year over-all program (NU, May '54, p. 78). AEC enters into the present experiments only in providing facilities for irradiation.

keting power in interstate commerce subject to Federal Power Act.

Stipulate that agreements for cooperation with other nations must specify duration, thus eliminating termination action by the President or Congress.

Authorize AEC to contract for electric utility services connected with Oak Ridge, Portsmouth, and Paducah operations, but contract must be submitted to Joint Committee for 30 days before taking effect.

Prohibit direct payment by AEC of contractor's income taxes.

Plans Underway for First Nuclear Society

Organizational details are now being completed for this country's first independent nuclear energy society, tentatively called the Society of Nuclear Scientists and Engineers. It will be a professional group that will be fully representative of all the scientific and engineering disciplines involved in the nuclear field.

First major activity of the group is to be a three-day conference in June, 1955, on the campus of Pennsylvania State University.

Two Meetings, Survey Planned by Atomic Forum

Impact of the Atomic Energy Act of 1954 on industry and opportunities for New England industry in atomic energy will be considered at two Atomic Industrial Forum meetings this fall. A survey is already underway to pinpoint future requirements for materials, equipment and skills in the atomic energy industry.

"The New Law: What It Means to You" will be discussed Sept. 27 and 28 in New York. Both government and industry will be represented on panels discussing interpretation and implementation of the new law, investment opportunities, the industrial future, the labor outlook, insurance problems, and government-industry cooperation.

A joint meeting with the New England Council in Boston, Mass., on Oct. 20 will consider "Atomic Opportunities in New England." Discussions will cover nuclear power development and by-product utilization. Lewis L. Strauss, chairman of the Atomic En-

Sidelights

Will construct aircraft nuclear engine test facility. AEC has asked for bids covering construction of an "exhaust system for the initial engine test area of the Aircraft Nuclear Propulsion project." Plans and specifications released last month call for a 150-ft reinforced concrete stack lined with fire brick, a reinforced concrete instrument vault, and about 200 ft of stainless-steel 6-ft-diameter duct to be erected at the National Reactor Testing Station in Idaho.

•

New Zealand's "geothermal" heavy-water project on again. Called off last year by Great Britain, a joint project for production of heavy water and electric power from geothermal steam bores at Wairakei (NU, Jan. '54, p. 74) has been reactivated. New Zealand's Prime Minister, Sidney Holland, announced in a budget speech that agreement has been reached with Britain's Atomic Energy Authority; plant will be designed in Britain.

•

"Official visitors" get Oak Ridge helicopter service. About an hour's travel time will be cut by new helicopter service from Knoxville, Tenn., airport to Oak Ridge. Shuttle service is available on a reservation basis for those traveling to Oak Ridge on official Atomic Energy Commission business.

•

Security wall down around MTR. Materials Testing Reactor at Arco, Idaho, is now an open facility, as evidenced by tour conducted for press representatives on August 20. Other facilities at the National Reactor Testing Station, including EBR and the prototype STR, remain classified areas.

•

Rolls Royce planning nuclear power. Two nuclear power experts have left Britain's Atomic Energy Research Center at Harwell to join Rolls Royce. Famous in the automobile industry, Rolls also pioneered development of jet engines for aircraft.

•

Liverpool synchrocyclotron working. Production of a 400-Mev proton beam has been achieved in the largest accelerator outside the United States.

•

Is Y-12 producing thermonuclear materials? The electromagnetic separations plant at Oak Ridge is undergoing reconstruction, reportedly as an addition to thermo-nuclear production facilities.

•

To test atmospheric effects on sound waves. A series of nonnuclear high-explosive tests will be carried out this fall at the Nevada Proving Grounds by AEC.

•

Durham, Hinshaw want medical reactors across country. At a recent Joint Congressional Committee on Atomic Energy hearing, Reps. Durham and Hinshaw went on record as being in favor of a series of reactors located throughout the country for medical therapy and research. Said Hinshaw, "We are getting to the point now of [needing to establish] these medical reactors.

•

What is actual cost of carbon-14? AEC sells radiocarbon for $32 a millicurie, but biological researchers must count on losing 10–20% in conversion (to acetate, for example) or pay $200 a millicurie for commercially available acetate. And body losses skyrocket amount needed for animal experiments—one small project with 5 or 10 animals can use up $3,000 of carbon-14. These facts were cited by Dr. N. T. Werthessen, Southwest Foundation for Research and Education, San Antonio, Texas, in asking Joint Congressional Committee on Atomic Energy to look into carbon-14 price structure. The Foundation spent $1,800 for carbon-14 last year, will spend $5,400 next.

ergy Commission, will be the principal speaker.

The three-part survey is being made under a study agreement with AEC. Results will be published later this year. Questionnaires mailed to 1,000 institutions, including 75 instrument manufacturers, will supply data for two survey sections, radiation instrument manufacture and private nuclear research and development. Data for the third section, reactor development, will be obtained by a review of AEC files, coupled with interviews with AEC contractors in its 5-year reactor program and participants in AEC's industrial participation program.

Dow-Detroit Study Gets $2.5-Million for '54

Of $2,555,000 contributed by supporting companies for 1954 operations, the Dow Chemical-Detroit Edison and Associates atomic-power-development project had allocated $1,651,000 by May 15. Largest allocation was $812,000 for research contracted with industrial firms; included is $75,000 for Ford Motor Co., first indication that this firm is actively engaged in nuclear engineering.

A summary of the group's allocations is given in the table on this page. A balance of $904,000 still is to be distributed for 1954 operations.

National Planning Group Awarded $200,000 Study

Ford Foundation has awarded $200,000 to the National Planning Association for a broad study of nonmilitary uses of atomic energy. Economics of industrial applications and power will be the primary study areas. Philip Mullenbach, former AEC Washington staff member, will direct the study.

Vitro Corp. Starts Power Processing Study

Number 14 in the Atomic Energy Commission industrial participation program for development of competitive nuclear power, Vitro Corporation of America's proposal recently approved by AEC is the first devoted to study chemical and metallurgical processing problems of nuclear power systems. Vitro Engineering Division will study preparation of fuel, removal of fission products, primary separation, recovery and reworking of unspent fuel, recovery and decontamination of fissionable material, and radioactive waste disposal.

First step in the one-year company-financed study is a survey of industrial power studies and AEC's reactor development program. One or more processing concepts will then be selected for engineering analysis, preliminary design studies, and cost estimates.

Colorado, Coast Groups Want Nuclear Power

Proposals for a cooperative-government nuclear power project in Colorado and a similar industry-government project in Washington State are on their way to Washington, D. C.

The Colorado State Association of REA Cooperatives has asked the state's Congressional delegation for

Allocation of 1954 Funds by Dow-Detroit Power-Study Project to Contracts and Commitments as of May 15

Recipient	*Allocated funds*	*Technical area*
Private facilities:		
Allis-Chalmers Manufacturing Co.	$111,000	Reactor mechanisms (control rod, core positioner); liquid-metal components
American Machine & Foundry Co.	110,000	Mechanical handling equipment
The Babcock & Wilcox Co.	75,000	Fuel-element fabrication, heat transfer, fuel and structural material, corrosion, heat exchangers
The Dow Chemical Co.	246,000	Fuel processing: alternate reactors
Ford Motor Co.	75,000	Fuel-element fabrication
Mine Safety Appliances Co.	33,000	Core container corrosion, heat transfer
Nuclear Development Associates, Inc.	146,000	Reactor physics calculations
University of Michigan	16,000	Fuel processing (aqueous)
Total private facilities	812,000	
Consultants:		
H. A. Bethe	17,000	Physics
H. J. Gomberg	(total)	Physics
L. P. Smith		Fuel material
G. H. Whipple		Health physics
AEC facilities:		
Argonne National Laboratory	*	Fuel processing, fast-reactor physics, liquid-metal components, irradiation testing
Battelle Memorial Institute	40,000	Fuel-element fabrication, alternate fuel materials, physical properties of fuels
Iowa State College	*	Fuel processing (pyro metallurgy)
Massachusetts Institute of Technology	75,000	Fuel-element fabrication
Total AEC facilities	115,000	
Project—Detroit working group:		
Cost of assigned personnel	587,000	
Estimated general expense	120,000	
Total, Detroit working group	707,000	
Total allocated project funds	1,651,000	
Total funds available	2,555,000	
Balance of project funds unallocated, May 15, 1954	904,000	

* Under consideration.

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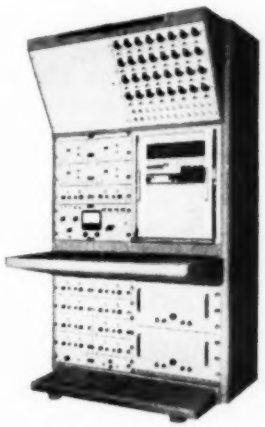

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NEW TELETHERAPY UNIT, designed for 10,000-curie cesium source, uses built-in computer for automatic control so that therapeutic procedures can be duplicated. Dr. Marshall Brucer, chairman of Oak Ridge Institute of Nuclear Studies' medical division where machine will be located, inspects 4½-ton unit at W. F. and John Barnes Co., the builders. Ceiling suspension on circular track enables unit to provide wide variety of radiation beam patterns

aid in obtaining Atomic Energy Commission financing of a proposed nuclear plant in that area. The Rural Electrification Administration had been asked to finance a conventional power plant for the Colorado Ute Electric Association, a group of four cooperatives. The new proposal would substitute a reactor for the conventional steam-generating apparatus, with AEC underwriting the added costs.

The proposal is based on the area's being a major source of uranium, but isolated and not fully served by a commercial utility. The Uranium Ore Producers Association has asked Sen. E. C. Johnson (D-Colo.) to back the proposed plant; 600 uranium-producing mines would be served by it.

In Washington State, the Puget Sound Utilities Council has decided to ask AEC if joint action in nuclear power development is feasible. The Council's idea is to extend proposed government partnership programs for hydroelectric projects to nuclear power. Represented on the Council are one private and four public power utilities in western Washington.

DIMPLE Operates: First British D_2O Reactor

DIMPLE (deuterium moderated pile, low energy) is now in operation at Britain's Atomic Energy Research Establishment, Harwell. Various types of fuel elements can be submerged in its heavy-water tank for design studies. The tank is surrounded by a graphite moderator.

First project is experimental work for E-443, a more powerful heavy-water reactor being built at Harwell to provide high neutron flux for research.

Operation of DIMPLE is restricted to very low power so that its structure does not become sufficiently radioactive to prevent the necessary handling of fuel arrays.

Navy Contracts for Two More Atom Subs

The 1955 ship-building program for the U. S. Navy includes construction of two more nuclear-powered submarines. Portsmouth naval shipyard, Kittery, Maine, will lay the keel of one this month. Navy's Bureau of Ships is negotiating with Electric Boat Division of General Dynamics Corp. for construction of the other at the firm's Groton, Conn., yards.

While no information has been released about power plants for these vessels, Knolls Atomic Power Laboratory and Argonne National Laboratory are designing an advanced reactor (SAR) to outperform existing types.

Research Reactors Draw 38 Inquiries

North American Aviation, one of a number of companies designing and building research and medical reactors, has received 38 inquiries to its atomic energy research department. Universities, research institutions, industrial firms, and potential foreign users who expressed interest in NAA research reactors were listed in recent testimony before the Joint Committee on Atomic Energy. Included were:

Universities. U. of California Medical Center, School of Engineering, and Radiation Laboratory; U. of Colorado; Columbia U.; MIT; Miami U.; U. of Michigan; U. of Minnesota; Pennsylvania State College; Purdue U.; State College of Washington; U. of Texas, Texas A and M; and U. of Utah.

Research institutions. Armour Research Foundation; Battelle Memorial Institute; Bell Telephone Laboratories; Brookhaven National Laboratory; Columbia Medical Center; Mayo Clinic; U. S. Naval Hospital, Bethesda, Md.; Office of Naval Research, Chicago; Watertown Arsenal; and Wright Air Development Center.

Industry. Mallinckrodt Chemical Works; North American Philips Co.; Standard Oil Development Co., Linden, N. J.; and Westinghouse Electric Corp.

Foreign. W. Caton, consulting engineer, Australia; French Embassy, Washington, D. C.; Chemisch-Technisches Institut, Der Rheinish-Westfalischen Technischen Hochschule, Aachen, Germany; Departmento Investigaciones Cientificas, Compania Energia Atomica, Argentina; U. of Mexico School of Medicine; R. K. Sas, Canada; Far East Mercantile Co., Japan; Laboratory of Nuclear Chemistry, Chalmers U. of Technology, Sweden; and Research Laboratorium Voor de Industrie, Technisch Natuurkundig Bureau Service, The Netherlands.

Chemists Top AEC List of Technical Employees

The Atomic Energy Commission and its operating contractors now employ 6,474 scientists and 7,138 engineers. Largest occupational group of the 13,612-man technical staff are chemists, totaling 2,411. The total staff consists of:

Biological, medical scientists	1,617
Chemists	2,411
Physicists	1,708
Other physical scientists	738
Chemical engineers	1,634
Electrical engineers	1,346
Mechanical engineers	1,843
Metallurgical engineers	408
Other engineers	1,907

Filling of 533 current vacancies would increase the staff to 14,145. But with vacancies unfilled, increase has been less than 1% in past year.

European Atomic Society Limits Memberships

Trying to concentrate on development of practical industrial uses of atomic energy, the European Atomic Energy Society (NU, July '54, p. 5) is limiting membership to nations that have already established nuclear energy projects. Eight nations—Belgium, France, Italy, The Netherlands, Norway, Sweden, Switzerland, and the United Kingdom—belong to this association of atomic energy commis-

NATIONAL RADIAC announces . . .

A Complete Scintillation Counter

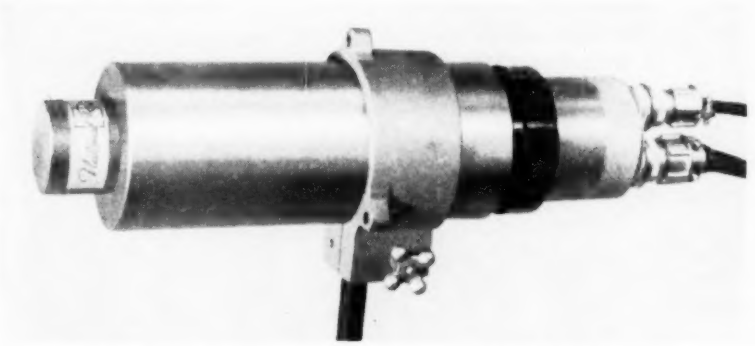
A versatile instrument for research, medical and industrial use.

One Standard Counter Fits All Accessories.

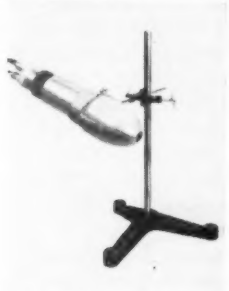
Accommodates any size, any type of National Radiac crystal detectors for measuring gamma, beta, alpha particles, neutrons and x-rays.

SCINTILLATION HEAD

Crystals, sealed in thin-walled containers, may be inserted directly in radiation beam. Uses 6292 or 5819 or 6342 photomultiplier tube and improved circuit. 100 ohm output impedance, permits up to 50 ft. of cable. Model SA-2 has self-contained, two-stage preamplifier with gain of ten. Easily provides 1 volt output pulses. Plateau slope is 3% per 100 v. Model SC-2 has cathode follower output. Plateau slope is 2% per 100 v.

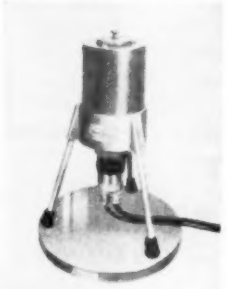


COLLIMATOR ATTACHMENT



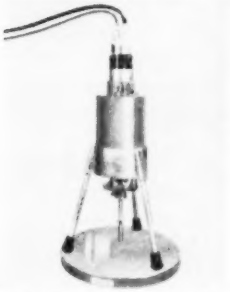
Model LC-2 Collimator Attachment mounted on scintillation counter. Includes large, one-inch diameter by one-inch long sodium iodide crystal for high sensitivity. Highly directional lead shield in front and behind crystal insures low background. Convenient adjustable camp and stand.

WELL TYPE SHIELD



Model LW-2 Shield Attachment holds scintillation counter and two-inch diameter well-type sodium iodide crystal. Provides full two inches of lead shielding in every direction, including below counter. Low background, high sensitivity. Crystal or counter instantly removable.

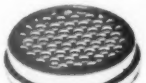
SAMPLE CHANGER



Model SM-2 Manual Sample Changer Attachment holds scintillation counter and crystal detectors. Provides two inches of lead shielding. Holds standard planchets.

A Complete Assortment of Crystal Radiation Detectors for Every Counting Need

Hermetically sealed, thin-walled containers. Optical glass windows. Transmits ultra violet. Interchangeable, permanent, light tight.



ALPHA COUNTER

Alpha particle counter. Light tight, insensitive to other radiations.

Hermetically sealed sodium iodide crystal. Best for gamma rays.

SODIUM IODIDE CRYSTAL

Sodium iodide, well type crystal. Has ¾ inch diameter by 1½ inch deep well.

WELL TYPE CRYSTAL

BETA COUNTER

Thin Stilbene single crystal, sensitive principally to Beta rays.

Also in sealed mountings, there are other Sintilon brand detectors which are interchangeable with the ones illustrated.

- **Lithium iodide crystal neutron counters.**
- **Boron loaded plastic, slow neutron counters (contains 20% boron).**
- **Proton recoil type, fast neutron counters.**
- **Organic scintillation crystals.**
- **Low cost plastic phosphors.**

Send for Bulletins 9 and 10 describing these.
Also handy file folder.

Specify Sintilon® brand crystals manufactured by

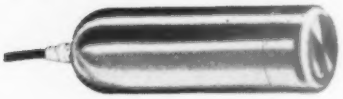
Department N-9

National Radiac **Inc.**

10 CRAWFORD ST. NEWARK, N.J.

VICTOREEN LABORATORY AND FIELD RATEMETERS

SENSITIVE SCINTILLATION...



SCINTILLATION PROBE

Victoreen scintillation probes are efficient — have greater sensitivity for the lower intensity ranges. Top quality 1″ by 1″ NaI(Tl) crystals used. Shock-mounted phototube optically coupled to crystal. Probe head removable for easy substitution of alpha or beta sensitive crystals — or larger 2″ by 1″ NaI(Tl) crystal. Water-tight case. Cable length varies.

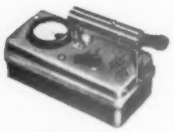
FIELD RATEMETER

The portable, compact and light-weight Victoreen Model 589F weighs less than 7 lbs. Single control. Three ranges of sensitivity — 0.05, 0.5 and 5.0 mr/hr. full scale. Sensitivity may be increased by readjustment. Fiberglas reinforced, rugged case. Two low-cost batteries used. Regulated vibrator power supply prevents calibration shift during battery aging.

LABORATORY RATEMETER

Victoreen Model 524A is AC powered. Calibrated in counts per minute. Six sensitivity ranges. Only three controls. Meter and loudspeaker rate reporting. Built-in recorder jack. Three time constants.

GM COUNTERS...



VICTOREEN MODEL 389C THYAC

The GM field-type ratemeter has a case identical with that shown at top of page. Time proven, reliable circuit. Single control. Meter and headphone rate reporting. Regulated vibrator power supply prevents calibration shift as batteries age. Selected by civil and military authorities.

ISOTOPE RATEMETER

Laboratory type. AC powered. The Victoreen Model 524 has six sensitivity ranges. Three controls. Three time constants. Calibrated in counts per minute. Meter and speaker rate indication. Built-in recorder jack.

This GM type probe has a thumb operated sliding shield for beta discrimination. Stainless steel shell; water-tight. Uses either the 1B85 or 6306 bismuth enriched counter tube. The 6306 is nearly six times as sensitive on I^{131}.

GM TYPE PROBE

Variations of the portable models are available for high sensitivity aerial and drill hole surveys.

Medical Instruments Division

The Victoreen Instrument Co.

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sions. Further memberships will be by invitation.

The society is planning its first conference for next summer.

Industry Can Save Billion with Isotopes, Says AEC

Present savings of about $100,000,000 a year by American industry through use of radioisotopes will expand to $1-billion in ten years. Atomic Energy Commission member Joseph Campbell made this prediction in a recent speech.

Citing current industrial uses of radioisotopes, Campbell pointed out several areas of large savings achieved by today's 860 industrial users.

Radiographic inspection of welded Hortonspheres for storing high-pressure gases saves about $6,000 per sphere.

Thickness gages are used by 300 companies. Larger companies report savings up to $100,000 annually in control of thickness of rubber, plastics, sheet steel, etc. Possible savings in control of copper sheet production, assuming 2% savings, are $9-million annually.

Tracer control of pipeline flow—using radioactivity to determine interface between shipments and thus avoid loss—is used by practically all pipeline carriers, saving an estimated $500,000 a year.

Leak detection eliminates breaking up concrete radiant-heated floors to find leaks. Campbell cited an instance where a residence heating bill shot up to $400 a month; radioiodine pinpointed the leak.

AEC, NSF Support Research; Fulbright Awards Continue

Government support of research and education is extended by three recent series of financial grants.

Universities and private research institutions have been awarded 90 contracts for unclassified physical research totaling almost $237,600 by the Atomic Energy Commission. National Science Foundation has announced 176 grants totaling about $1.1-million for basic research, conferences, information exchange, and travel to meetings. Government awards under the Fulbright Act have been increased by 326, for which applications are due October 15.

AEC awards include 12 new contracts: correlation of isotopic effect on reaction rate with reaction mechanism will be attempted at Illinois Institute of Technology; isotope effect in chemical reactions will be studied at Okla-

Where AEC's Instrument Dollar Goes

NEARLY FIVE TIMES as much is spent by the Atomic Energy Commission and its contractors to buy instruments from commercial sources than is spent in building them within the project. Figures given in illustration are based on accounting study of AEC's $13-million instrument inventory and $10-million fiscal-1953 purchases

homa A & M; mechanism of graphitization, at Pennsylvania State University; radiation-induced solid-state polymerization, at Polytechnic Institute of Brooklyn; design of low-power reactor, at State College of Washington; paramagnetic resonance absorption, at University of Chicago; kinetic and equilibrium salt effects, at Cornell University; preparation and properties of technetium and rhenium compounds, at University of North Carolina; remodeling electrostatic generator, at University of Notre Dame; transfer of ORNL Cockcroft-Walton, to Vanderbilt University; interaction of polarized photons with matter, at University of Virginia; and quantum mechanical and semi-empirical determination of intermolecular forces, at University of Wisconsin.

AEC contracts for 78 research projects at several universities were renewed.

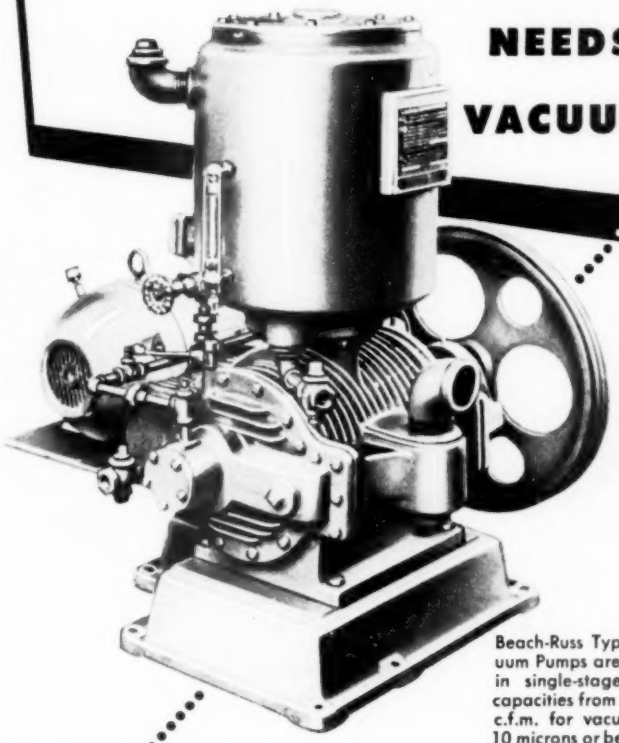
Included in the NSF grants were $3,100 in support of a conference on radiation biochemistry sponsored by the National Academy of Sciences.

Further information on the postdoctoral Fulbright awards can be obtained from the Conference Board of Associated Research Councils, Committee on International Exchange of Persons, 2101 Constitution Ave., Washington 25, D. C.

Nuclear Pedagogy Gains in Two Eastern Schools

Expansion of nuclear engineering curricula in two eastern colleges is evidenced by recent appointments:

Wherever NUCLEAR RESEARCH OR PRODUCTION NEEDS VACUUM....



Beach-Russ Type RP Vacuum Pumps are available in single-stage units in capacities from 20 to 1700 c.f.m. for vacuum up to 10 microns or better. Compound stages are also available.

on operations requiring absolute pressures in the micron range in the lab, the pilot plant or the production phase . . .

BEACH-RUSS Type RP HIGH VACUUM PUMPS

. . . because of their fast pump-down ability, have established their effectiveness both individually and as fore-pumps in a wide range of vacuum processing.

Capacities from 20 to 1700 C.F.M.

All Beach-Russ units are designed and constructed to give noiseless and vibrationless operation . . . low power consumption and operating costs.

RP PUMP CATALOG 90 carries full details. Write for a copy.

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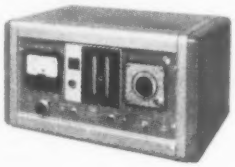
Address Department 66

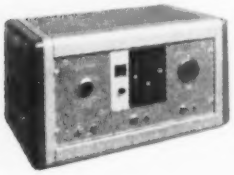
TMC

SCALERS REDUCE COINCIDENCE LOSS!*

SG-1A The COMPLETE Scaler — 1 or 20 millivolt maximum sensitivity—5 electronic decades—Auto-count—Auto-time—extra stable, dual range high voltage power supply — 2 to 2.5 microsecond resolving time.

SG-2A Auto-time scaler — one millivolt non-blocking printed circuit amplifier with Schmitt discriminator — scaler of 100 or 1000 — extra stable high voltage power supply — 2 to 2.5 microsecond resolving time.





SG-3A Research scaler with 2 to 2.5 microsecond resolving time — scale of 1000 — instantaneous reset — calibrated precision Schmitt discriminator.

* All Tmc scalers have 2 to 2.5 microsecond resolving times, resulting in ½ of 1% maximum coincidence loss at 120,000 C.P.M.

TMC

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Remarkable performance in the

TWO-STAGE DUO-SEAL® VACUUM PUMP

deal for backing up Diffusion Pumps
GUARANTEED VACUUM—0.0001 mm (0.1 Micron)
FREE AIR CAPACITY—375 Liters Per Minute
SPEED—185 Liters Per Minute at 1 Micron Pressure

Exceptionally Quiet Operation

Built-in Trap prevents oil from backing up into system.

Indicator window shows oil level at all times.

Convenient oil drain permits oil change without dismantling system.

COMPACT
Size 26 x 14½ x 18½ inches

Booth No. 743–745
I.S.A. Exposition
Philadelphia, Pa.
Sept. 15–21

Patent No. 2337849

No. 1397-B
COMPLETE $575.00
Write for new pump catalog

Manufacturers of Scientific Instruments and Laboratory Apparatus

W. M. WELCH SCIENTIFIC COMPANY
DIVISION OF W. M. WELCH MANUFACTURING COMPANY
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New York University has hired Lyle Borst to head the department of physics in its college of engineering. Borst headed reactor work at Brookhaven and most recently was on the University of Utah faculty.

Rensselaer Polytechnic Institute, Troy, N. Y., has hired V. Lawrence Parsegian to be chairman of its engineering group and professor of nuclear engineering. Parsegian formerly directed research division of AEC's New York Operations Office.

During the last academic year, 193 college science and engineering teachers listed themselves under "atomic energy" in a University of Chicago Press census of 61,351 educators.

Reorganization Causes More AEC Changes

Continuing its large-scale revamping, (NU, June '54, p. 76) the Atomic Energy Commission has reconstituted the San Francisco area office as an operations office reporting directly to the director of military applications in Washington. Dr. Harold Fidler continues as the office's manager.

Merrill S. Eisenbud, formerly director of AEC's New York health and safety laboratory, is the new manager of the New York operations office. Its former manager, Henry B. Fry, has become assistant manager for administration and services in the Santa Fe operations office at Albuquerque, N. M. Ralph P. Johnson has succeeded R. E. Cole as assistant manager for engineering, construction and test operations at the Santa Fe office.

Grace M. Wells has been appointed director of public information service at the New York operations office. She replaces John F. Hogerton, who resigned to rejoin Vitro Corp., New York. Prior to joining NYOO in 1949, Miss Wells was on Brookhaven National Laboratory's public relations staff.

At Oak Ridge, Tenn., AEC's operations office established a new Feed Materials Division to direct and coordinate research and production programs transferred from NYOO. F. R. Dowling, deputy assistant manager for operations, will direct the new unit.

The vacancy created when Allan C. Johnson was advanced to manager of the Idaho operations office last May, has been filled by appointment of Herbert M. Leppich as director of the office's division of engineering and construction. Mr. Leppich was a project engineer in the Idaho office.

RAW MATERIALS

Madagascar. Covering 600 square miles, deposits of high grade uranium and thorium ore have been discovered in southwestern Madagascar at Behara-Esira. Ore is mixture of thorium oxides in uranium oxides. , French atomic energy commission (CEA), sole legal buyer, will pay about $1.25 per pound of ore. Madagascar is already exploiting other ore deposits near Antsirabe, as well as beryl and thorium sands.

NEWSMAKERS

Gordon R. Molesworth, formerly director of the nuclear energy information division of Bozell & Jacobs, Inc., has organized the public relations and advertising firm of Molesworth Associates, 261 Madison Ave., New York. The firm will deal exclusively with atomic energy and related fields. Mr. Molesworth was at one time assistant to the manager of AEC's Oak Ridge Operations Office.

Robert Holmes has been named director of Atomic Bomb Casualty Commission in Japan. The appointment was announced by the National Academy of Sciences, National Research Council.

John W. Cartinhour, formerly deputy director of engineering for Foster Wheeler Corp., has been named manager of the New York firm's Nuclear Energy Department, recently created for nuclear-reactor development.

Maj. Gen (ret.) Herbert Bernard Loper has succeeded **Robert LeBaron** as chairman of the Military Liason Committee to the AEC.

Gordon Dean, former chairman of the Atomic Energy Commission, has been elected a director of General Dynamics Corp. The corporation has also announced appointment of **Frederick H. Warren** as assistant to the executive vice president, atomic energy.

Harvard L. Hull has been named president of Farnsworth Electronics Co. of Fort Wayne, Ind., a new division of International Telephone and Telegraph Corp. The new division will take over and expand industrial electronics and nucleonics research and manufacturing from the Capehart-Farnsworth Co. division. Dr. Hull, before joining the latter organization last year, was director of remote control engineering at Argonne National Laboratory.

target tomorrow

As a major development in its pace-setting program of advance planning, the Martin Aircraft Company is now in the field of nuclear power.

This means that a top team of scientists, physicists and engineers is about to be assembled at Martin to carry on a planned, long-range program in this tremendous new science.

Never before in our industry has there been such an opportunity for a select group of qualified people.

They will be the nucleus of a major undertaking in the horizonless science of atomic energy.

Write to J. M. Hollyday, Department N-9, The Glenn L. Martin Company.

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PRODUCTS AND MATERIALS

18 Firms Display Variety of Equipment at First Large-Scale Nuclear Engineering Exhibit

Industry's eagerness to shift into high gear on nuclear engineering development was evident among the 18 firms that exhibited at the American Institute of Chemical Engineers' International Nuclear Engineering Congress held at Ann Arbor, Michigan, last June 20–25. Complete reactors were offered by three exhibitors—and others were eager to supply everything from special laboratory and reactor equipment to contract research.

American Machine & Foundry Co., Babcock & Wilcox Co., and Foster Wheeler Corp., all of New York City, showed models of the swimming-pool-type research reactors they are ready to build for industry and universities. Babcock & Wilcox also offers a water-boiler-type liquid-fuel reactor.

Minneapolis-Honeywell Regulator Co., of Philadelphia, Pa., supplies a complete automatic control and instrument console package for reactors, chemical processes, and laboratories. El-Tronics, Inc., also of Philadelphia, Radiation Counter Laboratories, Inc., Skokie, Ill., and Tracerlab, Inc., Boston, Mass., furnish radiation-detecting and -measuring devices for laboratories and reactors.

A Detroit firm, R. V. Harty Co., designs and constructs radiological hot cells and shields. In conjunction with Michigan Chemical Corp., St. Louis, Michigan, they also supply zinc-bromide viewing windows. Shielding glass and special glass for use with $ZnBr_2$ solutions are supplied by Corning Glass Works, Corning, N. Y. Kewaunee Manufacturing Co., Adrian, Mich., offers a varied line of dry boxes, safety hoods, and stainless-steel laboratory equipment. S. Blickman, Inc., Weehawken, N. J., specializes in fabricating various alloys into unusual shapes and systems. Master-slave remotely-controlled manipulators are supplied by Central Research Laboratories, Inc., Red Wing, Minn.

The Atomic Equipment Dept. (Cheswick, Pa.) of Westinghouse's Atomic Power Div. manufactures canned-rotor pumps and special equipment for reactors. Callery Chemical Co., Callery, Pa., supplier of sodium-potassium alloy, also makes conduction-type a-c electromagnetic pumps and flowmeters. The Pfaudler Co., Rochester, N. Y., produces a line of chemical processing equipment made of carbon steel with fused-glass working surfaces. National Lead Co., N. Y. C., supplies, processes, and fabricates basic metals for atomic energy applications. Battelle Memorial Institute, Columbus, O., performs all phases of nuclear energy research for government and industry.

The following equipment and services were exhibited:

American Machine & Foundry Co. AMF expects to quote firm prices on research reactors soon. A model of a swimming-pool type reactor showed how AMF's standardized units can be used interchangeably to give various reactor configurations. Eventually, AMF intends to have a catalog from which components can be selected.

AMF also has developed reactor control mechanisms. A control-rod drive (with associated servo amplifier) and a reactor safety device were exhibited.

The rack-and-pinion drive for the control rod incorporates a low-inertia motor and a dual synchro system for accurate positioning. Three-bolt mounting permits rapid replacement. Drive, amplifier, and fault-detection units can be tested for improper operation and are said to be maintained easily.

The safety element is positioned by a gear motor, an internal computing mechanism, and a cable drum. A magnetic dry-powder clutch is designed to provide quick release and smooth deceleration.

Babcock & Wilcox Co. A firm price between $100,000 and $150,000, depending on specifications and installation problems, will buy a 1-Mw swimming-pool reactor or a 200–400 kw water-boiler reactor made by B&W. Models and plans of each reactor were exhibited.

The water boiler is a semihomogeneous unit with an aqueous enriched-uranium sulfate fuel solution. The core is in the center of a 4-ft cube of graphite used as a reflector. A 4-in.-thick carbon-steel thermal shield surrounds this. A 5-ft extension of the graphite reflector on one side serves as a thermal column. Aluminum exposure ports extend to the core or reflector from all faces of the octagonal high-density concrete shield. There are two ports in the thermal column. The B&W water-boiler reactor is designed to supply strong collimated beams of both thermal and mixed neutrons for experimental uses. Large through-holes with fairly high fluxes can be provided.

Configuration of the swimming-pool reactor, located in water in a $10 \times 20 \times 25$-ft concrete tank, and experimental facilities can be varied to permit many types of experiments. In addition to eight 6-in. and two 8-in. beam ports, B&W plans to incorporate three pneumatic tubes for fast "rabbit" experiments. Special ports and tubes also can be provided.

Foster Wheeler Corp. Models of a swimming-pool type research reactor and a chemical processing plant were displayed in Foster Wheeler's exhibit. The firm's nuclear engineering department plans to design and build reactors and other equipment to order.

Minneapolis-Honeywell Regulator Co. Recorders and control instruments were shown in the Minneapolis-Honeywell display. One available unit is an automatic control and instrument console. For reactors, the firm supplies the complete control circuit except for the detectors and rods.

El-Tronics, Radiation Counter Labs, and Tracerlab. These three firms displayed radiation survey meters, monitors, ion chambers, and scalers. El-Tronics also showed servo amplifiers

and electronic test equipment. RCL also exhibited gamma spectrometers and compensated ion chambers for measuring neutron flux. Tracerlab demonstrated their manual and automatic sample-counting equipment.

R. V. Harty Co. This engineering contracting firm showed a $ZnBr_2$ shielding window of the type the firm supplies for hot cells. Harty will design and build concrete shields for hot cells and other applications.

Corning Glass Works. Corning exhibited special refractories and various types of glass for shielding, dosimetry, and laboratory apparatus.

Corning supplies the nuclear field with three main types of transparent shielding glass: 3.27-gm/cm³ cerium-stabilized lead glass, 6.25-gm/cm³ Pb glass, and a 2.7-gm/cm³ Ce-stabilized calcium glass that is recommended for containing $ZnBr_2$ shielding solutions.

Special-composition glasses developed by Corning include a radiation-damage-resistant 100%-silica glass and dosimeter formulations for personnel protection and quality control in food sterilization. A variety of shapes and sizes are available.

Corning makes special refractories for high-temperature applications in which corrosion resistance is important. For example, their dense alumina is a nonreacting container for molten uranium. Other Corning refractories include: stabilized zirconia, zircox (zirconium silicate), and chromic oxide.

Kewaunee Manufacturing Co. This laboratory furniture manufacturer exhibited devices for handling various hazardous chemical, biological, and radioactive materials. Standard units and accessories can be combined for various operations involving many steps with the different types of hazardous materials. Rubber gloves or remotely-controlled manipulators are used to perform work inside the units. The boxes can be supplied with built-in lead shields. Most units are portable and can be moved to designated decontamination areas.

S. Blickman, Inc. Blickman showed illustrations of complex laboratory equipment and processing systems the firm has custom-fabricated. Blickman shapes various alloys (including stainless steel, aluminum, and nickel) into dry boxes, hoods, and other laboratory equipment. The firm also fabricates circuits for liquid-metal coolants.

Central Research Laboratories, Inc. The Model-4 master-slave manipulator was demonstrated in the Central Research Lab. exhibit. It provides easier sight control and more sensitive "touch" than the firm's previous models. Central Research Lab. also performs contract research in the fields of chemistry, physics, and electronics.

Westinghouse Atomic Equipment Dept. Westinghouse displayed a 5,000-gal/min canned-rotor pump designed to pump high-temperature fluids where zero leakage is essential. The pump's Inconel-jacketed rotor turns inside a similarly-clad stator for protection from the fluid. Bearings are lubricated by the fluid being pumped.

Callery Chemical Co. Conductor-type electromagnetic pumps designed to operate to 1,000° F from single-phase 60-cycle a-c voltages were exhibited. They have no moving parts, no packing glands, and can be installed with weld or flange connections. The flow is fully reversible and rate control is 100% from zero to maximum.

Callery's electromagnetic flowmeter also was shown. It is said to be accurate to ±2%, and is designed for use with fluid temperatures up to 1,500° F. It has a relatively high fluid capacity with straight-through flow, a straight line-voltage:flow-rate relationship, and has no moving parts, seal pots, diaphragms, or gages.

Callery supplies NaK in any composition desired.

Pfaudler Co. Pfaudler displayed piping components and valves from its line of fused-glass chemical processing equipment. The special cobalt-glass fused to the surface of carbon steel is intended to make the equipment resist acid corrosion up to 450° F. The glass surface exerts no measurable catalytic effect and resists product adherence. The equipment is said to be easy to clean, durable, and economical.

National Lead Co. Samples of metals processed and fabricated by National Lead Co. were exhibited. Lead safes and bricks of various shapes were shown.

National Lead also can supply complete reactor fuel elements as well as other fabricated products made of: lead, titanium, uranium, zirconium, barium, nickel, cobalt, and thorium.

Battelle Memorial Institute. Battelle-developed materials of importance in reactor construction were featured in the Institute's exhibit. The arc-melting process for producing zirconium was demonstrated.

In the nuclear field, Battelle engages in research on: reactor systems, effects of radiation, tracer techniques, uranium and thorium beneficiation and metallurgy, heat transfer, thermodynamics, corrosion, and engineering economics.

THESE ARE NOT ALL the firms that design and manufacture nuclear equipment. Only products and services of companies exhibiting at the Congress are reported. A complete listing of suppliers of nuclear equipment and materials is given in the NUCLEONICS Buyers' Guide published each November.

New Products This Month

Radioactivity Monitor

The model 1619 monitor was designed for use with a Geiger counter for (1) routine surveying for alpha, beta or gamma contamination in radioisotope laboratories, (2) detecting large fluctuations in cosmic ray and other laboratory "background," and (3) other routine measurements of radioactivity for medical work, tracer work or process control in industry. The instrument provides four ranges for counts up to 20,000 cpm. A built-in loudspeaker is provided for additional indication. *Nuclear Instrument & Chemical Corp., 229 W. Erie St., Chicago 10, Ill.* (P-1)

Compressor Amplifier

The type 501-A compressor amplifier stabilizes varying signals to eliminate adjusting levels when oscilloscope, bridges, phase-comparator or wave-analyzer signals are observed. Instrument accepts signals of varying amplitudes between 1.25 and 50 volts and delivers an output signal of the same

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Research and Development

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Lockheed

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research and engineering staff

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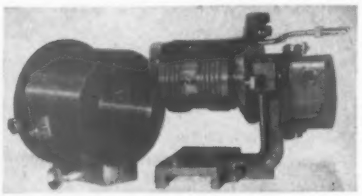
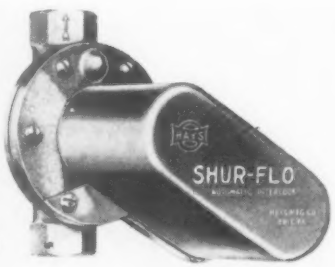
waveform but held at a substantially constant amplitude of 0.25 volt (0.4 db) by a servo-controlled distortionless variable attenuator. Compression ratio is 40 to 1 (32 db) from 500 cycles to 1 Mc, but slightly less below 500 cycles. Frequency range for complex signals at any condition of compression is 50 cycles to 50 kc. *Technology Instrument Corp., Acton, Mass.* (P-2)



X-Ray Diffraction Camera

The model HC-101 high-temperature X-ray diffraction powder camera was designed for general-purpose investigations of substances at controlled elevated temperatures up to 1,000° C. Movable film carrier allows five 7-mm diffraction patterns to be made on the same film, facilitating the determination of phase diagrams and registering comparison patterns of different substances at selected temperatures. Film carrier can be removed from the furnace assembly at any stage of investigation without disturbing the thermal environment of powder sample. Standard 35-mm X-ray film may be used for single exposures. *Central Research Laboratories, Inc., Red Wing, Minn.* (P-3)

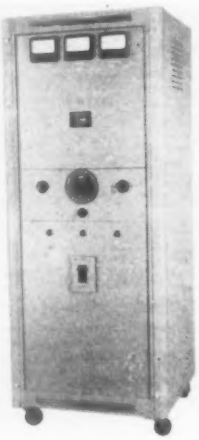


Automatic Flow Switch

The Shur-Flo Automatic Interlock flow switch cuts off equipment or provides a signal wherever flow falls below established safety rate. Available in $\frac{1}{2}$-and $1\frac{1}{4}$-in. pipe sizes. The $\frac{1}{2}$-in. size provides switch control points anywhere from 0.1 to 8 gal/min and $1\frac{1}{4}$-in. size provides switch control points anywhere from 8 through 40 gal/min. *Hays Mfg. Co., 812 W. 12th St., Erie, Pa.* (P-4)

Electronic Counter

The model 524B direct-reading automatic electronic counter employs four plug-in units to extend range, increase sensitivity or provide time-interval measuring circuits. Basic range of unit is 10 cps to 10 Mc for frequency counting or 0–10 kc for period measurement. Video amplifier, frequency converter and time-interval plug-in units extend the counter's capabilities so that it measures frequency from 10 cps to 220 Mc and time interval from 1 μsec to 100 days. Time interval measurements are said to have an accuracy of 0.1 μsec ± 0.001%. *Hewlett-Packard Co., Dept. P, 395 Page Mill Rd., Palo Alto, Calif.* (P-5)

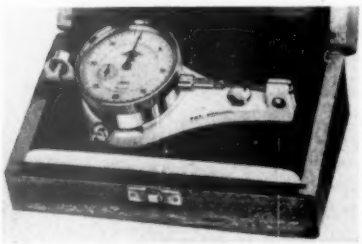


Electronic Generator

The model 1425 electronic generator delivers 900 VA power output from 80 to 135 volts or 160 to 270 volts. Four frequency ranges covering 50–6,000 cycles are provided. Distortion is <5% at full load; no-load to full-load voltage regulation is within 2%. *Communication Measurement Laboratory, Inc., 350 Leland Ave., Plainfield, N. J.* (P-6)

Electrophoresis Unit

The Series 54 Electrograf accommodates 20 $\frac{1}{2}$-in.-wide filter strips or 12 1-in.-wide filter strips. The unit has voltage control from zero to 450 volts and current control from zero to 50 ma. The power supply has sufficient capacity, and is equipped with necessary plug-ins, to operate four migrating chambers simultaneously. Migrating chamber fits into any refrigerator to maintain constant temperatures. Constant humidity is created with snug-fitting cover. Separate troughs are used for electrodes and buffer for protecting migrating material. Cotton wicks connect the electrode troughs with buffer; automatic liquid leveler prevents syphoning buffer through paper. *Labline, Inc., 217–221 N. Desplaines St., Chicago 6, Ill.* (P-7)



Dimension Gage

The JKA dial comparator is used for quick, accurate dimension readings of very small parts. To take measurements, the operator moves the operating lever to the right, opening the jaws and disks; after the part is in position, the operating lever is released and a direct reading appears on the dial. The unit is supplied with a range of zero to 10 mm, with 0.01-mm graduations, or 0–$\frac{7}{16}$ in. with 0.0005-in. graduations. *Mercury Supply Co., 410 Fairview, Elmhurst, Ill.* (P-8)

Air and Gas Dehydrator

The model Cm-1 dehydrafilter is a small desiccant air and gas dehydrator designed especially for isolated pneumatic equipment. It is rated at 1 cfm at 100 psig and 70° F. The dehydrator features a disposable desiccant cartridge and "O" ring seal construction that eliminates the need for tools to

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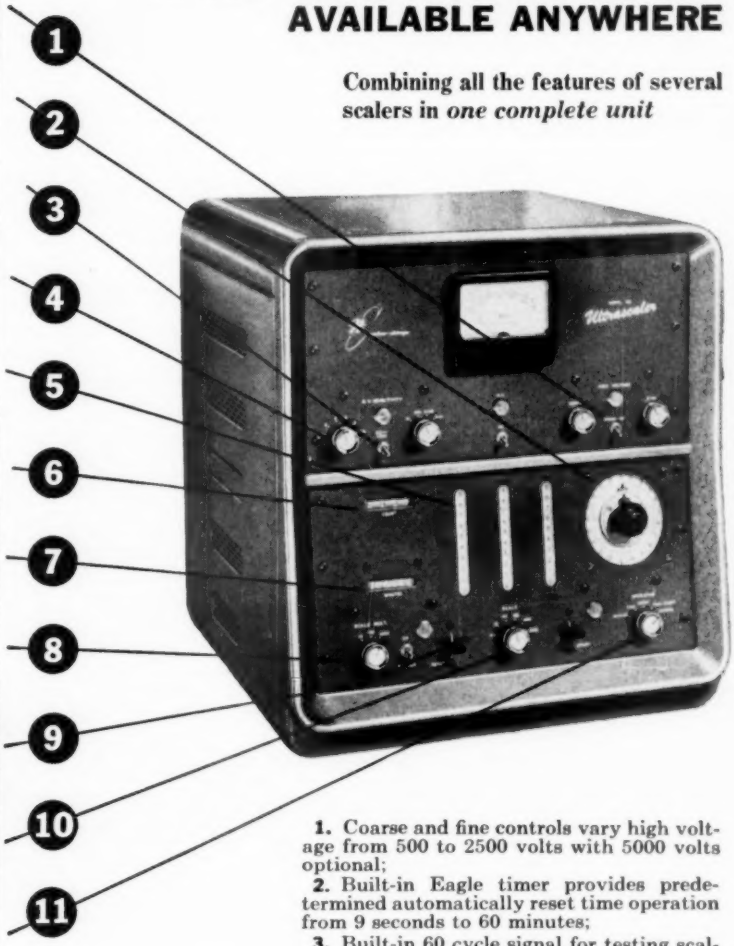

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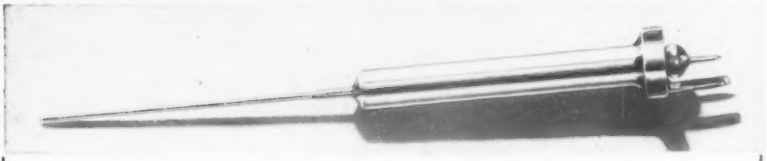

LELAB GEIGER-MUELLER TYPE COUNTER TUBES

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Except for a glass bead insulator, Lelab counter tubes are constructed entirely of metal. The metal cylinder is used both as the envelope and cathode of the tube—providing it with strength, resistance to shock and simplicity of design.

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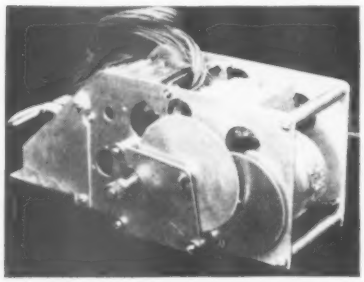
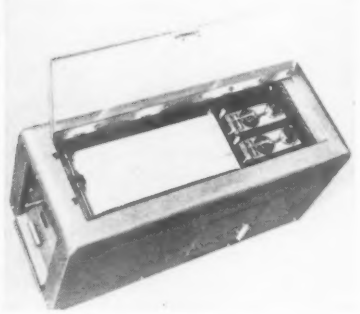
change the cartridge. It will provide dew points as low as −67° F. Materials used in the construction of the dehydrafilter are brass for the head and case and plastic-coated aluminum for the cartridge. Right or left hand units are available. *Hankison Corp., Pittsburgh, Pa.* (P-9)



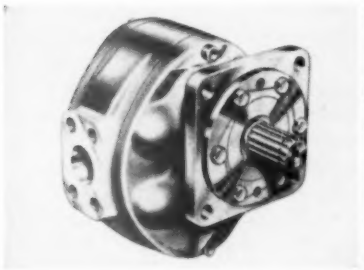
Digital Converter

The Digi-Coder converts analog output of primary sensing devices, such flow meters, thermocouples or pressure transducers, into a digital signal. Digital signals are represented by discrete contact positions in the coder. Two Digi-Coder types are offered. One converts mechanical motion, delivered to its input shaft from a pneumatic or other receiving mechanism, into a digital output signal; torque requirements are less than 0.2 in.-oz. Second type, which contains an integral self-balancing potentiometer, converts analog voltage into the digital signal. Voltage-input type operates on 0–1 mv input and up. *Fischer & Porter Co., Hatboro, Pa.* (P-10)



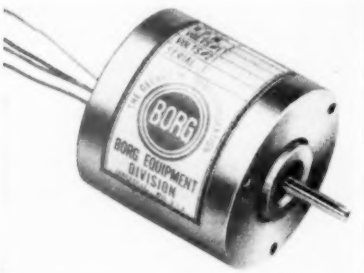
Oscillograph Recorder

Model 8082 two-channel oscillograph recorder can be shifted easily to any one of six speeds, from $2\frac{1}{2}$ to 100 mm/sec while unit is operating or turned off. Deposited-metal drive roll and positive nonslip paper adjustments permit use of rolled or folded paper. Instrument transcribes in ink, drawn through nonclog ink system on true circulinear coordinates. *Edin Co., Inc., 207 Main St., Worcester 8, Mass.* (P-11)



Hydraulic Pumps

The series H pressure-balanced, oil-hydraulic, gear-type pumps, designed for heavy-duty use in machine tools, materials handling, earth moving and other mobile equipment, deliver 40, 50, 60 and 70 gal/min at 1,200 rpm, and operate at pressures up to 1,500 lb/in.^{2} Port connections are made by means of SAE split-flange hose connections. These pumps can be easily removed for servicing without destroying piping seals or developing leaks. *Hydreco Div., New York Air Brake Co., 1100 E. 222nd St., Cleveland 17, Ohio.* (P-12)

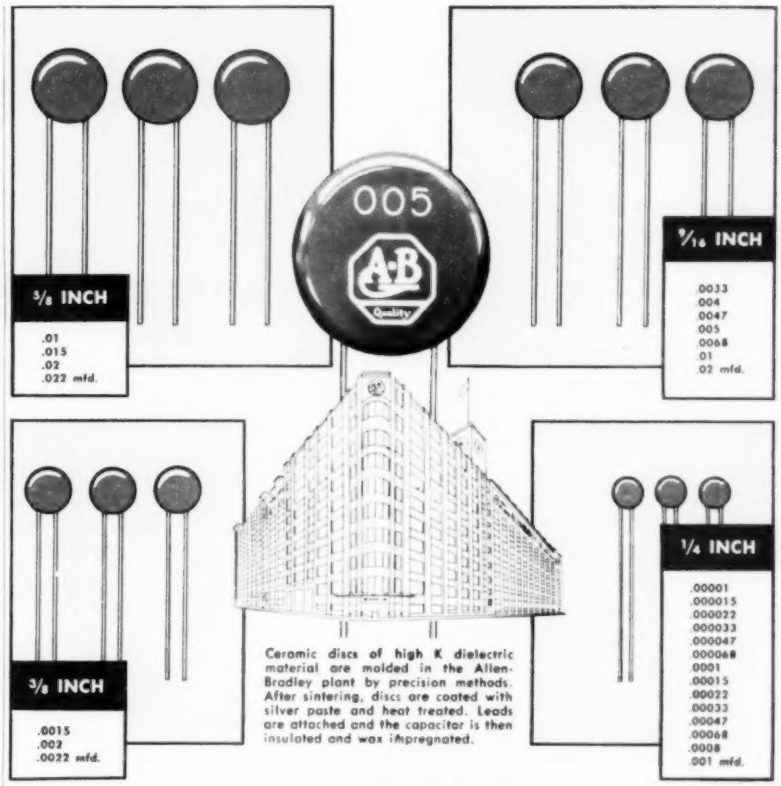


Servo Motor

Model 1050 servo control motor is designed to operate Borg micropots but can be used in many other servo applications. It is a 115-volt, 400-cps 2-phase induction-type motor. The 1050 has a 5,500 rpm no-load speed and its minimum locked rotor torque is 0.82 oz-in. in either direction. *George W. Borg Corp., Janesville, Wis.* (P-13)

Power Oscillator

Power oscillator model 1040, designed for use as a power source for bridges and test set-ups, provides a frequency



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of either 400 or 1,000 cps. Three watts of power, at less than 1% distortion, are provided at various output impedance levels. A control on the front panel allows for a continuously variable output from zero to 120 volts. Frequencies are factory set to within 0.25%. *Industrial Test Equipment Co., 55 E. 11th St., New York, N. Y.* (P-14)

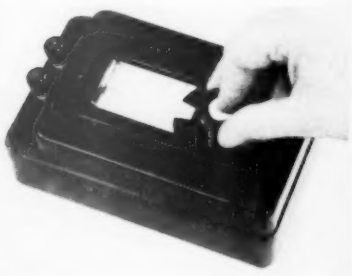
Digital Computer

The model 203 digital computer is a general-purpose machine that is said to be adaptable to any problem reducible to numerical terms. Mathematical functions are performed at an average rate of 500/sec except multiplication and division, which are accomplished at 120/sec and 85/sec, respectively. Average access time to words stored in the main part of the magnetic memory drum is 8.5 msec, while those stored in the temporary section can be delivered in an average of 0.85 msec. *Consolidated Engineering Corp., 300 N. Sierra Madre Villa, Pasadena 8, Calif.* (P-15)

High-Speed Framing Camera

Model 222 framing camera, designed for use in combustion, corona-discharge, explosion, plastic- and elastic-deformation and shock-wave phenomena, produces high-resolution photographs at rates as high as 2.4 million/sec. Similar but lower speed model 189 covers the range up to 1.2 million frames/sec. Effective aperture of the film is approximately f/14.5. Resolution in time direction is 50 lines/mm, and 100 lines/mm in the space direction; exposure time, established by diamond-aperture stops, in the standard camera is 3×10^{-7} sec at 5,000 rps. Frame size is $^3/_4$ by 1 in.; focus range of objective lens is 7 ft to infinity. Integrated into camera housing is a day-

light-loading magazine with 100-ft capacity, hand-crank-operated take-up mechanism and film-footage indicator. *Beckman & Whitley, Inc., 974 San Carlos Ave., San Carlos, Calif.* (P-16)



Wheatstone Bridge

Type ZK single-knob measuring bridge, covering six resistance ranges from 40 milliohms to 50,000 ohms, operates with standard 4.5-volt dry cell. *Herman H. Sticht Co., Inc., 27 Park Pl., New York, N. Y.* (P-17)

Dealkalizing Salt Splitter

For small and medium-sized plants, the Dealkalizer utilizes strongly basic anion exchange resin capable of salt splitting and substituting chloride anions for bicarbonate, carbonate, sulfate and nitrate radicals. It is claimed that this process of chloride anion exchange greatly reduces alkalinity without use of acids, reduces CO_2 in steam and provides continuous treatment under pressure. *Cochrane Corp., 17th St. and Allegheny Ave., Philadelphia 32, Pa.* (P-18)

Analog-Digital Converter

The analog-digital converter was designed for use in data handling systems or digital computers to simplify and speed up analog-digital conversion. Time sharing of control circuits is possible for multichannel systems by using

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Shown above is one of the many applications on which the "Airbrasive" process has been successfully used. In this case, the problem was to drill contact depressions .030" in diameter and .015" deep in a quartz disc. With the "Airbrasive" process, this was just another routine operation!

The "Airbrasive" process has solved many such "problem" jobs for electronics manufacturers — many of them considered impossible to do by conventional means. It has proved to be highly successful in cutting germanium and other hard, brittle materials—in "trimming" resistance elements on printed circuits—in removing deposited surface coatings — and in shaping fragile crystals used in neutron diffraction work.

Perhaps you have a similar problem. Why not arrange for a demonstration at our New York or California office. Or — if you prefer — we'll conduct tests on your samples and advise you as to the suitability of the process for your needs.

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isolation diodes in series with each pickoff brush, allowing the control circuit to be used for scanning many converters. Standard code disks are manufactured for binary operation, but Gray, decimal or other systems may be ordered. Present models include 7, 13, 17 and 19 digit units, all 2 in. in diam, varying from 2 $^{49}/_{64}$ to 4 $^{13}/_{16}$ in. long. Input requirements are input torque under 0.2 oz-in. and current of 2 ma/pickoff brush. Digit output frequency may vary from 500 cps to 1 Mc or higher. *Librascope, Inc., 1607 Flower St., Glendale, California.* (P-19)

Automatic Valve

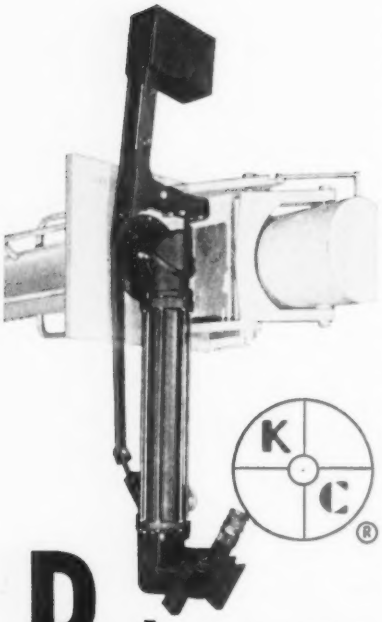
The Electroflo Valve utilizes a piston-type pilot-action solenoid-operated valve to provide automatic on-off control of water or air flow. *Hays Mfg. Co., 814 W. 12th St., Erie, Pa.* (P-20)

Analytical Quartz Shapes

Commercial quartz shapes are available for micro and ultramicro analytical work. Items include breakers, boats, flasks, graded seals, ground joints and capillary pipets. They are transparent and provide high transmission of ultraviolet and visible radiations. Melting point and chemical resistance are high. *Microchemical Specialties Co., 1834 University Ave., Berkeley, Calif.* (P-21)

Silicone O-Rings

Kel-F-coated silicone rubber O-rings provide resistance to aromatic, chlorinated or other solvents that normally attack silicone rubber. Useful temperature range is approximately −120° F to +390° F. Low-temperature properties of silicone rubber are not affected. *Bacon Industries, Inc., 192 Pleasant St., Watertown, Mass.* (P-22)



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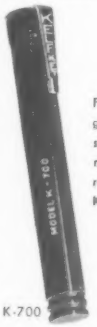
POCKET CHAMBERS



K-700 Pocket Chamber
(AEC #PIC-2E)

For monitoring exposure to X-or gamma radiation. Completely sealed, unit is unaffected by atmospheric conditions. 200 mr. range. 4¼" x ½" dia. charged on K-430A Charge-Reader.

K-300 Slow Neutron Pocket Chamber
(AEC #PIC-5J)

Measures exposure to slow or thermal neutrons. Use for monitoring areas or source carrying containers in transit. Also to plot isodose line. 200 mr. range. 4¼" x ½" dia. charged on K-430A Charge-Reader.

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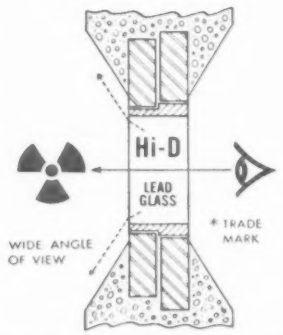
Hi-D*

LEAD GLASS WINDOWS IN CONCRETE WALLS



Hi-D Lead Glass Windows in concrete walls are dry, and hence are completely dependable. Where the viewing problem is mainly wide-angle vision, Hi-D Glass is fully competitive in price with zinc bromide.

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INDUSTRY NOTES

▶**Isotope Products Inc.,** is being formed in Buffalo, N. Y., to provide radiographic inspection equipment for industry.

▶**National Lead Co.,** New York, has established a radiochemical laboratory within its research laboratories. In addition to research, the new unit will provide radiographic and industrial tracer tests for the company's plant.

▶**Babcock & Wilcox Co.,** New York, has contracted with Westinghouse Electric Corp. to supply two heat exchangers for the PWR power plant to be built near Shippingport, Pa. The exchangers embody less expensive materials in a design requiring fewer complex shop operations than previous units of the same type.

▶**Stone & Webster Engineering Corp.,** New York, has been selected by Brookhaven National Laboratory as architect-engineer of building and supporting facilities for the 25-Bev proton sychrotron. Funds for the $20-million accelerator project have been approved by the Atomic Energy Commission.

LITERATURE AVAILABLE

Vacuum tube voltmeter. Brochure describes electrometer model 210. *Keithley Instruments, 3868 Carnegie Ave., Cleveland 15, Ohio.* (L-1)

Thermoelements. "Thermoelements Noble and Base Metals" discusses reliability and use of thermocouples. *Charles Englehard, Inc., 850 Passaic Ave., East Newark, N. J.* (L-2)

Electron microscopes. Folder gives characteristics and applications of models EM-75 and EM-100 electron microscopes. *North American Philips Co., Inc., 750 S. Fulton Ave., Mt. Vernon, N. Y.* (L-3)

High-voltage resistors. Bulletin G-1 describes type MV high-voltage resistors. *International Resistance Co., 401 N. Broad St., Philadelphia 8, Pa.* (L-4)

Industrial waste treatment. Advantages inherent in treatment of industrial waste waters and process liquors are described in bulletin WC-116. *Graver Water Conditioning Co., 216 W. 14th St., New York 11, N. Y.* (L-5)

Germanium diodes. Bulletin N-1 gives comprehensive data on series 1N germanium diodes. *International Resistance Co., 401 N. Broad St., Philadelphia 8, Pa.* (L-6)

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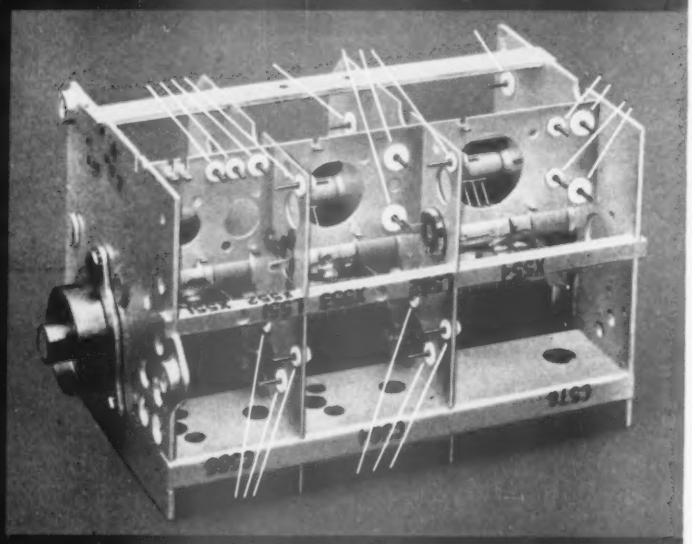

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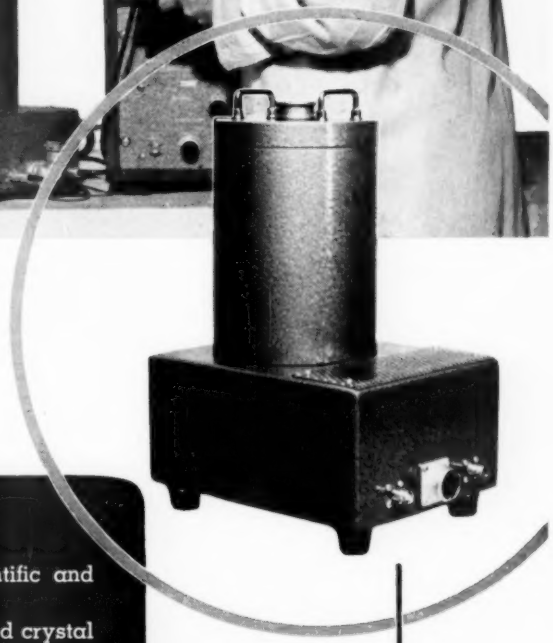
The Model 810 Scintillation Counter, powered by Atomic's Model 312 Precision High Voltage Supply, has a linear output which feeds into a Model 218 Linear Amplifier, a Model 510 Single Channel Pulse Height Analyzer, and a Model 1030A Scaler for pulse height analysis research.



MODEL 810

model 810

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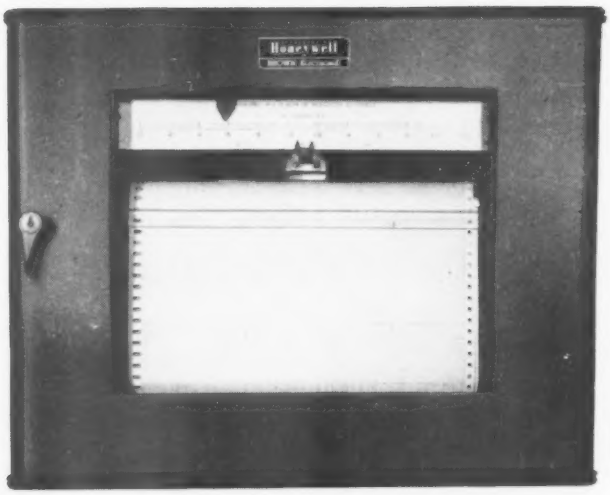
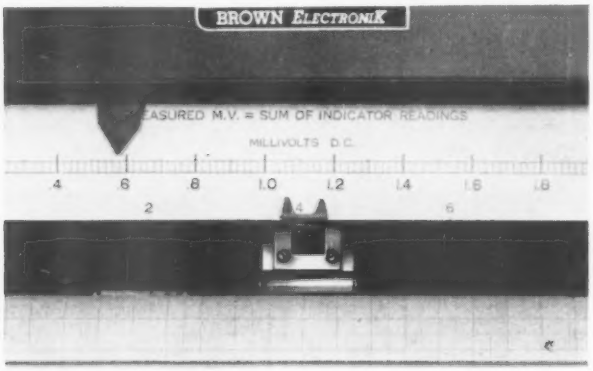


Now...the answer to high-resolution recording of test data

... *the* Extended Range *ElectraniK* Recorder



Closeup of indicating scale. Upper pointer shows millivolts within the span; lower pointer indicates millivolts to be added. Total reading: 4.58 mv.

DESIGNED especially for recording variables which change over a wide range, this new *ElectroniK* instrument records on a chart effectively *55 inches in width*. It has five equal measuring spans. Whenever the variable being measured reaches either the upper or lower limit of one of these ranges, the instrument automatically steps to the adjoining range and continues recording.

Two indicating pointers show the range in use and the value within the range. Connected to each pointer is a pen; one draws a purple record showing the range, the other draws a red record of the variable itself. To get the complete reading, you simply add both pen or pointer indications.

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